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THE POWER OF ARC CONSISTENCY FOR CSPS DEFINED BY PARTIALLY-ORDERED FORBIDDEN PATTERNS

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ABSTRACT. Characterising tractable fragments of the constraint satisfaction problem (CSP) is an important challenge in theoretical computer science and artificial intelligence. Forbidding patterns (generic sub-instances) provides a means of defining CSP fragments which are neither exclusively language-based nor exclusively structure-based. It is known that the class of binary CSP instances in which the broken-triangle pattern (BTP) does not occur, a class which includes all tree-structured instances, are decided by arc consistency (AC), a ubiquitous reduction operation in constraint solvers. We provide a characterisation of simple partially-ordered forbidden patterns which have this AC-solvability property. It turns out that BTP is just one of five such AC-solvable patterns. The four other patterns allow us to exhibit new tractable classes.

1. INTRODUCTION

The *constraint satisfaction problem* (CSP) provides a common framework for many theoretical problems in computer science as well as for many real-life applications. A CSP instance consists of a number of variables, a domain, and constraints imposed on the variables with the goal to determine whether the instance is satisfiable, that is, whether there is an assignment of domain values to all the variables in such a way that all the constraints are satisfied.

The general CSP is NP-complete and thus a major research direction is to identify restrictions on the CSP that render the problem *tractable*, that is, solvable in polynomial time.

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A substantial body of work exists from the past two decades on applications of universal algebra in the computational complexity of and the applicability of algorithmic paradigms to CSPs. Moreover, a number of celebrated results have been obtained through this method; see [2] for a recent survey. However, the algebraic approach to CSPs is only applicable to *language-based* CSPs, that is, classes of CSPs defined by the set of allowed constraint relations but with arbitrary interactions of the constraint scopes. For instance, the well-known 2-SAT problem is a class of language-based CSPs on the Boolean domain $\{0, 1\}$ with all constraint relations being *binary*, that is, of arity at most two.

On the other side of the spectrum are *structure-based* CSPs, that is, classes of CSPs defined by the allowed interactions of the constraint scopes but with arbitrary constraint relations. Here the methods that have been successfully used to establish complete complexity classifications come from graph theory [28, 33].

The complexity of CSPs that are neither language-based nor structure-based, and thus are often called *hybrid* CSPs, is much less understood; see [9, 20] for recent surveys. One approach to hybrid CSPs that has been rather successful studies the classes of CSPs defined by *forbidden patterns*; that is, by forbidding certain generic subinstances. The focus of this paper is on such CSPs. We remark that we deal with *binary* CSPs but, unlike in most papers on (the algebraic approach to) language-based CSPs, the domain is *not* fixed and is part of the input.

An example of a pattern is given in Figure 1(a) on page 5. This is the so-called *broken triangle* pattern (BTP) [16] (a formal definition is given in Section 2). BTP is an example of a *tractable* pattern, which means that the class of all binary CSP instances in which BTP does not occur is solvable in polynomial time. The class of CSP instances defined by forbidding BTP includes, for instance, all tree-structured binary CSPs [16]. There are several generalisations of BTP, for instance, to quantified CSPs [26], to existential patterns [10], to patterns on non-binary constraints [18], and other classes [34, 17].

The framework of forbidden patterns is general enough to capture language-based CSPs in terms of their polymorphisms. If Γ is a finite set of (binary) constraint relations, then $\text{CSP}(\Gamma)$ is the set of instances whose constraint relations all belong to Γ . It is well known that a necessary condition for $\text{CSP}(\Gamma)$ to be tractable (assuming $P \neq NP$) is that Γ has a non-trivial polymorphism [8]. For any given a polymorphism f , the framework of forbidden patterns is general enough to capture the class of (binary) CSP instances $\text{CSP}(\Gamma_f)$, where Γ_f is the set of (binary) constraint relations closed under f , provided patterns can be enriched by the function f (or an equivalent relation) on domain elements. For instance, the pattern in Figure 1(b) on page 5 captures the notion of binary relations that are max-closed [30].

Surprisingly, there are essentially only two classes of algorithms (and their combinations) known for establishing tractability of CSPs. These are, firstly, a generalisation of Gaussian elimination [7, 22], whose applicability for language-based CSPs is known [29], and, secondly, problems solvable by *local consistency methods*, which originated in artificial intelligence; see references in [35]. The latter can be defined in many equivalent ways including pebble games, Datalog, treewidth, and proof complexity [25]. Intuitively, a class of CSP instances is solvable by k -consistency if unsatisfiable instances can always be refuted while only keeping partial solutions of size k “in memory”. For instance, the 2-SAT problem is solvable by local consistency methods.

For structure-based CSPs, the power of consistency methods is well understood: a class of structures can be solved by k -consistency if and only if the treewidth (modulo homomorphic equivalence) is at most k [1]. Consequently, consistency methods solve all

tractable cases of structurally-restricted bounded-arity CSPs [28]. For language-restricted CSPs, the power of consistency methods has only recently been characterised [3, 6].

Contributions. Our ultimate goal is to understand the power of local consistency methods for hybrid CSPs. On this quest, we focus in this article on the power of the first level of local consistency, known as *arc consistency* (AC), for classes of binary hybrid CSPs defined by forbidden (partially-ordered) patterns.

The class of CSPs defined by forbidding BTP from Figure 1(a) on page 5 is in fact solvable by AC. But as it turns out, BTP is not the only pattern with this property.

As our main contribution, we give, in Theorem 5.5, a *complete characterisation* of so-called simple partially-ordered forbidden patterns which have this AC-solvability property. Here the partial orders are on variables and domain values. It turns out that BTP is just one of five such AC-solvable patterns. The four other patterns allow us to exhibit new tractable classes, one of which in particular we expect to lead to new applications since it defines a strict generalisation of binary max-closed constraints which have already found applications in computer vision [21] and temporal reasoning [23]. We also provide results on the associated meta problem of deciding whether a CSP instance falls into one of these new tractable classes.

Given that AC is the first level of local consistency methods¹ and is implemented in *all* constraint solvers, an understanding of the power of AC is paramount. We note that focusing on classes of CSPs defined by forbidden patterns is very natural as AC *cannot* introduce forbidden patterns because pattern occurrence is defined by the presence of some compatibility and incompatibility pairs between values, and by definition, such pairs cannot be added when values are removed. While simple patterns do not cover all partially-ordered patterns it is a natural, interesting, and broad enough concept that covers BTP and four other novel and non-trivial tractable classes. We expect our results and techniques to be used in future work on the power of AC.

Related work. Computational complexity classifications have been obtained for binary CSPs defined by forbidden negative patterns (i.e., only pairwise incompatible assignments are specified) [13] and for binary CSPs defined by patterns on 2 constraints [15]. Moreover, (generalisations of) forbidden patterns have been studied in the context of variable and value elimination rules [10]. Finally, the idea of forbidding patterns as topological minors has recently been investigated [11].

[31, 36] recently considered the possible extensions of the algebraic approach from the language to the hybrid setting.

The power of the valued version of AC [14] has recently been characterised [32]. Moreover, the valued version of AC is known to solve all tractable finite-valued language-based CSPs [37].

¹In some AI literature AC is the second level, the first being *node consistency* [35]. AC is also the first level for *relational width* [5].

2. PRELIMINARIES

2.1. CSPs and patterns. A pattern can be seen as a generalisation of the concept of a binary CSP instance that leaves the consistency of some assignments to pairs of variables undefined.

Definition 1 . A pattern is a four-tuple $\langle X, D, A, \text{cpt} \rangle$ where:

- X is a finite set of variables;
- D is a finite set of values;
- $A \subseteq X \times D$ is the set of possible variable-value assignments called points; the domain of $x \in X$ is its non-empty set $D(x)$ of possible values: $D(x) = \{a \in D \mid \langle x, a \rangle \in A\}$;
- cpt is a partial compatibility function from the set of unordered pairs of points

$$\{\{\langle x, a \rangle, \langle y, b \rangle\} \mid x \neq y\}$$

to $\{\text{TRUE}, \text{FALSE}\}$. If $\text{cpt}(\langle x, a \rangle, \langle y, b \rangle) = \text{TRUE}$ (resp., FALSE) we say that $\langle x, a \rangle$ and $\langle y, b \rangle$ are compatible (resp., incompatible). For simplicity, we write $\text{cpt}(p, q)$ for $\text{cpt}(\{p, q\})$.

We will use a simple figurative drawing for patterns. Each variable will be drawn as an oval containing dots for each of its possible points. Pairs in the domain of the function cpt will be represented by lines between points: solid lines (called *positive*) for compatibility and dashed lines (called *negative*) for incompatibility.

Example 1 . The pattern in Figure 13 on page 16 is called *LX*. It consists of three variables, five points, six positive edges, and two negative edges.

We refine patterns to give a definition of a CSP instance.

Definition 2 . A binary CSP instance P is a pattern $\langle X, D, A, \text{cpt} \rangle$ where cpt is a total function, i.e. the domain of cpt is precisely $\{\{\langle x, a \rangle, \langle y, b \rangle\} \mid x \neq y, a \in D(x), b \in D(y)\}$.

- The relation $R_{x,y} \subseteq D(x) \times D(y)$ on $\langle x, y \rangle$ is $\{\langle a, b \rangle \mid \text{cpt}(\langle x, a \rangle, \langle y, b \rangle) = \text{TRUE}\}$.
- A partial solution to P on $Y \subseteq X$ is a mapping $s : Y \rightarrow D$ where, for all $x \neq y \in Y$ we have $\langle s(x), s(y) \rangle \in R_{x,y}$.
- A solution to P is a partial solution on X .

For notational simplicity we have assumed that there is *exactly one* binary constraint between each pair of variables. In particular, this means that the absence of a constraint between variables x, y is modelled by a complete relation $R_{x,y} = D(x) \times D(y)$ allowing every possible pair of assignments to x and y . We say that there is a *non-trivial* constraint on variables x, y if $R_{x,y} \neq D(x) \times D(y)$. We also use the simpler notation R_{ij} for R_{x_i, x_j} .

The main focus of this paper is on ordered patterns, which additionally allow for variable and value orders.

Definition 3 . An ordered pattern is a six-tuple $\langle X, D, A, \text{cpt}, <_X, <_D \rangle$ where:

- $\langle X, D, A, \text{cpt} \rangle$ is a pattern;
- $<_X$ is a (possibly partial) strict order on X ; and
- $<_D$ is a (possibly partial) strict order on D .

A pattern $\langle X, D, A, \text{cpt} \rangle$ can be seen as an ordered pattern with empty variable and value orders, i.e. $\langle X, D, A, \text{cpt}, \emptyset, \emptyset \rangle$.

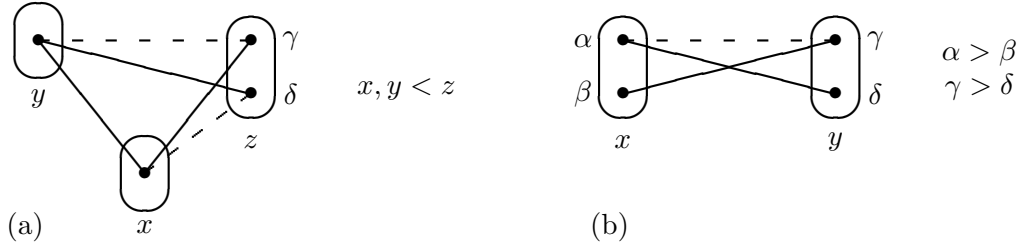


Figure 1: Two AC-solvable patterns: (a) BTP (b) MC.

Throughout the paper when we say “pattern” we implicitly mean “ordered pattern” and use the word “unordered” to emphasize, if needed, that the pattern in question is not ordered.

We do not consider patterns with structure (such as equality or order) between elements in the domains of *distinct* variables.

Definition 4 . A pattern $P = \langle X, D, A, \text{cpt}, <_X, <_D \rangle$ is called basic if (1) $D(x)$ and $D(y)$ do not intersect for distinct $x, y \in X$, and (2) $<_D$ only contains pairs of elements $\langle a, b \rangle$ from the domain of the same variable, i.e., $a, b \in D(x)$ for some $x \in X$.

Example 2 . The pattern shown in Figure 1(a) is known as the broken triangle pattern (BTP) [16]. BTP consists of three variables, four points, three positive edges, two negative edges, $<_X = \{x < z, y < z\}$, and $<_D = \emptyset$. Given a basic pattern, we can refer to a point $\langle x, a \rangle$ in the pattern as simply a when the variable is clear from the context or a figure. For instance, the point $\langle z, \gamma \rangle$ in Figure 1(a) can be referred to as γ .

Example 3 . The pattern in Figure 1(b) is the (binary) max-closed pattern (MC). The pattern MC consists of two variables, four points, two positive edges, one negative edge, $<_X = \emptyset$, and $<_D = \{\beta < \alpha, \delta < \gamma\}$. MC (Figure 1(b)) together with the extra structure $\alpha > \beta$ is an example of a pattern that is not basic.

For some of the proofs we will require patterns with additional structure, namely, the ability to enforce certain points to be distinct.

Definition 5 . A pattern with a disequality structure is a seven-tuple $\langle X, D, A, \text{cpt}, <_X, <_D, \neq_D \rangle$ where:

- $\langle X, D, A, \text{cpt}, <_X, <_D \rangle$ is a pattern; and
- $\neq_D \subseteq D \times D$ is a set of pairs of domain values that are distinct.

An example of such a pattern is given in Figure 21(b) on page 24.

2.2. Pattern occurrence. Some points in a pattern are indistinguishable with respect to the rest of the pattern.

Definition 6 . Two points $a, b \in D(x)$ are mergeable in a pattern $\langle X, D, A, \text{cpt}, <_X, <_D \rangle$ if there is no point $p \in A$ for which $\text{cpt}(\langle x, a \rangle, p)$, $\text{cpt}(\langle x, b \rangle, p)$ are both defined and $\text{cpt}(\langle x, a \rangle, p) \neq \text{cpt}(\langle x, b \rangle, p)$.

Definition 7 . A pattern is called unmergeable if it does not contain any mergeable points.

Example 4 . The points γ and δ in BTP (Figure 1(a) on page 5) are not mergeable since they have different compatibility with, for instance, the point in variable x . The pattern LX (Figure 13 on page 16) is unmergeable.

Some points in a pattern (known as dangling points) are redundant in arc-consistent CSP instances and hence can be removed.

Definition 8 . Let $P = \langle X, D, A, \text{cpt}, <_X, <_D \rangle$ be a pattern. A point $p \in A$ is called dangling if it is not ordered by $<_D$ and if there is at most one point $q \in A$ for which $\text{cpt}(p, q)$ is defined, and furthermore (if defined) $\text{cpt}(p, q) = \text{TRUE}$.

Example 5 . The point β in the pattern MC (Figure 1(b) on page 5) is not dangling since it is ordered.

In order to use (the absence of) patterns for AC-solvability we need to define what we mean when we say that a pattern *occurs* in a CSP instance. We define the slightly more general notion of occurrence of a pattern in another pattern, thus extending the definitions for unordered patterns [15]. Recall that a CSP instance corresponds to the special case of a pattern whose compatibility function is total. Essentially pattern P occurs in pattern Q if P is homomorphic to a subpattern of Q via an injective renaming of variables and a (possibly non-injective) renaming of points [13]. We first make the observation that dangling points in a pattern provide no useful information since we assume that all CSP instances are arc consistent, which explains why dangling points can be eliminated from patterns.

Definition 9 . A pattern is simple if it is (i) basic, (ii) has no mergeable points, and (iii) has no dangling points.

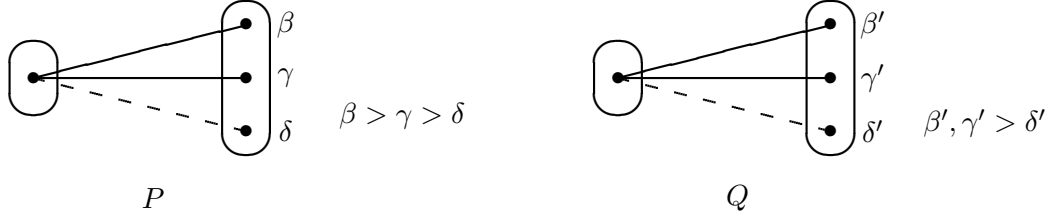
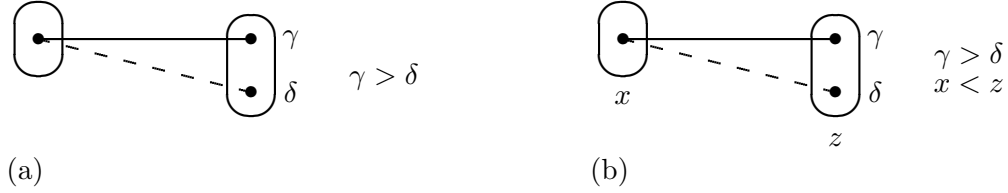
From a given pattern it is possible to create an infinite number of equivalent patterns by adding dangling points or by duplicating points. By restricting our attention to simple patterns we avoid having to consider such patterns. We also discount non-basic patterns and mergeable patterns partly because of the sheer number of cases to consider and partly because most of these patterns are not very natural.

Definition 10 . Let $P' = \langle X', D', A', \text{cpt}', <_{X'}, <_{D'} \rangle$ and $P = \langle X, D, A, \text{cpt}, <_X, <_D \rangle$ be two patterns. A homomorphism from P' to P is a mapping $f : A' \rightarrow A$ which satisfies:

- If $\text{cpt}'(p, q)$ is defined, then $\text{cpt}(f(p), f(q)) = \text{cpt}'(p, q)$.
- The mapping $f_{\text{var}} : X' \rightarrow X$, given by $f_{\text{var}}(x') = x$ if $\exists a', a$ such that $f(\langle x', a' \rangle) = \langle x, a \rangle$, is well-defined and injective.
- If $x' <_{X'} y'$ then $f_{\text{var}}(x') <_X f_{\text{var}}(y')$.
- If $a', b' \in D'(x')$, $a' <_{D'} b'$, $f(\langle x', a' \rangle) = \langle x, a \rangle$ and $f(\langle x', b' \rangle) = \langle x, b \rangle$ then $a <_D b$.

A consistent linear extension of a pattern $P = \langle X, D, A, \text{cpt}, <_X, <_D \rangle$ is a pattern P^t obtained from P by first identifying any number of pairs of points p, q which are both mergeable and incomparable (according to the transitive closure of $<_D$) and then extending the orders on the variables and the domain values to total orders.

Definition 11 . Let $P' = \langle X', D', A', \text{cpt}', <_{X'}, <_{D'} \rangle$ and $P = \langle X, D, A, \text{cpt}, <_X, <_D \rangle$ be two patterns. P' occurs in P if for all consistent linear extensions P^t of P , there is a homomorphism from P' to P^t . We use the notation $\text{CSP}_{\overline{\text{SP}}}(P)$ to represent the set of binary CSP instances in which the pattern P does not occur.

Figure 2: Two patterns: Q occurs in P , but P does not occur in Q .Figure 3: Two subpatterns of EMC: (a) $V^>$ (b) $V^<$

Thus, $I \in \text{CSP}_{\overline{\text{SP}}}(P)$ (the set of instances in which pattern P does not occur as a subpattern) if one can find a total ordering of the variable-set and the domain of I so that the pattern P is not homomorphic to I equipped with these orders.

The definition of occurrence extends in a natural way to patterns with a disequality structure.

Remark 2.1. We can add $a \neq b$ to a pattern, without changing its semantics, when $b <_D a$ or $\langle x, a \rangle$ and $\langle x, b \rangle$ are joined by negative and positive edges to some point $\langle y, c \rangle$. Furthermore, all domain values a, b in an instance are distinct so there is an implicit $a \neq b$.

Example 6 . To illustrate the notion of consistent linear extension used in the definition of occurrence, consider the two patterns P, Q shown in Figure 2. For P to occur in Q we would require that there is a homomorphism from P to Q after any number of mergings in the domain of Q and any extension of the domain ordering of Q to a total ordering: this effectively corresponds to the three cases $\beta' < \gamma'$, $\beta' = \gamma'$ and $\beta' > \gamma'$. Since there is not a homomorphism from P to the version of Q in which β' and γ' have been merged, we can deduce that P does not occur in Q . On the other hand, Q occurs in P and, indeed, Q occurs in the pattern $V^>$ shown in Figure 3(a) since β' and γ' can both map to γ .

As another example, the pattern MC (Figure 1(b) on page 5) occurs in pattern EMC (Figure 5 on page 10) but not in patterns BTP (Figure 1(a) on page 5) or BTX (Figure 9 on page 14).

The main positive result in this paper is that $\text{CSP}_{\overline{\text{SP}}}(\text{EMC})$ is solved by arc consistency. In the following example we give generic examples of instances in $\text{CSP}_{\overline{\text{SP}}}(\text{EMC})$.

Example 7 . $\text{CSP}_{\overline{\text{SP}}}(\text{MC})$ is exactly the set of binary CSP instances in which all constraints are max-closed [30]. Examples of such constraints are binary constraints of the form $y \geq F(x)$ for any function F or constraints of the form $x \geq G(y)$ for any function G .

$\text{CSP}_{\overline{\text{SP}}}(\text{EMC})$ includes all instances in $\text{CSP}_{\overline{\text{SP}}}(\text{MC})$ but also other instances. For example, if $I \in \text{CSP}_{\overline{\text{SP}}}(\text{MC})$, then we can create an instance $I' \in \text{CSP}_{\overline{\text{SP}}}(\text{EMC})$ which extends I by adding some constraints which are not max-closed: in fact for each variable y of

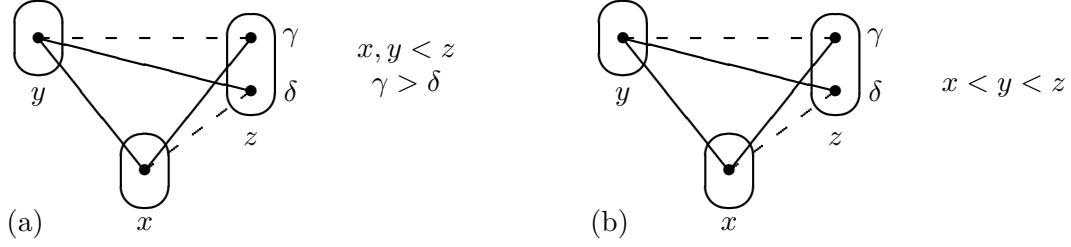


Figure 4: Two equivalent versions of the broken triangle property: forbidding the pattern (a) BTP^{do} or forbidding the pattern (b) BTP^{vo} defines the same class of instances.

I we can add new variables z_y^1, \dots, z_y^r in I' with arbitrary constraints on (y, z_y^i) ($i = 1, \dots, r$) provided that each z_y^i ($i = 1, \dots, r$) is placed after y in the variable ordering of I' and each z_y^i is constrained by no other variable.

As another example of an instance I'' in $\text{CSP}_{\overline{\text{SP}}}(\text{EMC})$, again let $I \in \text{CSP}_{\overline{\text{SP}}}(\text{MC})$ and let $J \in \text{CSP}_{\overline{\text{SP}}}(\text{V}^>)$ where $\text{V}^>$ is the pattern shown in Figure 3(a). Constraints in J are of the form $x \leq F(y)$ where F is an antitone function, i.e. $y_1 < y_2 \Rightarrow F(y_1) \geq F(y_2)$. We combine I and J to create the instance I'' . We first order the variables of I, J so that all the variables of I lie before all the variables of J . To complete the description of I'' , we add constraints between variables in I and variables in J so that the pattern $\text{V}^>$ (shown in Figure 3(b)) does not occur with x mapping to a variable of I and z mapping to a variable of J . Such constraints are of the form $z \leq G(x)$ where G is any function. The resulting instance I'' belongs to $\text{CSP}_{\overline{\text{SP}}}(\text{EMC})$.

For a pattern P , we denote by $\text{unordered}(P)$ the underlying unordered pattern, that is,

$$\text{unordered}(\langle X, D, A, \text{cpt}, <_X, <_D \rangle) = \langle X, D, A, \text{cpt} \rangle.$$

For instance, the pattern $\text{unordered}(\text{BTP})$ is the pattern from Figure 1(a) on page 5 *without* the structure $x, y < z$.

The occurrence relation between patterns is transitive.

Lemma 2.2. *If P occurs in Q and Q occurs in R , then P occurs in R .*

Proof. Suppose that P occurs in Q and Q occurs in R . Since Q occurs in R , for all consistent linear extensions R^c of R , there exists a homomorphism $h : Q \rightarrow R^c$. We will first construct a consistent linear extension Q^c of Q based on R^c and h . The set of variables of R^c is totally ordered (by definition of a consistent linear extension). Since, by Definition 10, the mapping h_{var} induced by h on the variables of Q to the variables of R^c is injective, there exists a total ordering $<_{X_{Q^c}}$ of the variables X_Q of Q corresponding to the total ordering $<_{X_{R^c}}$ in R^c of the variables $h_{\text{var}}(X_Q)$ (i.e. $x <_{X_{Q^c}} y$ if and only if $h_{\text{var}}(x) <_{X_{R^c}} h_{\text{var}}(y)$).

Now, consider any variable x in the pattern Q and any pair of points a, b in the domain $D_Q(x)$ of x in Q . First, consider the case when a, b are non-mergeable. By Definition 6 and Definition 10, the points $h(\langle x, a \rangle), h(\langle x, b \rangle)$ are also non-mergeable. For each such pair a, b , define $a <_{D_{Q^c}} b$ if and only if $a' <_{D_{R^c}} b'$ where $h(\langle x, a \rangle) = \langle x', a' \rangle$, $h(\langle x, b \rangle) = \langle x', b' \rangle$ and $<_{D_{R^c}}$ is the order on the domain values of R^c . This order is defined for each pair of non-mergeable values a, b since R_c is a consistent linear extension. Secondly, consider the case when a, b are mergeable. If $h(\langle x, a \rangle) = h(\langle x, b \rangle)$ or if $h(\langle x, a \rangle), h(\langle x, b \rangle)$ are merged in

the consistent linear extension R^c , then we merge a, b in Q^c ; otherwise we define $a <_{D_{Q^c}} b$ if and only if $a' <_{D_{R^c}} b'$ where $h(\langle x, a \rangle) = \langle x', a' \rangle$, $h(\langle x, b \rangle) = \langle x', b' \rangle$.

Let Q_c be identical to the pattern Q but with the variable and domain orders $<_{X_{Q^c}}$ and $<_{D_{Q^c}}$ as defined above. By construction, Q_c is a consistent linear extension of Q and there exists a homomorphism $h' : Q_c \rightarrow R_c$. Since P occurs in Q , we know that there exists a homomorphism $g : P \rightarrow Q^c$. The composition of g and h' is then a homomorphism from P to R^c . Since R^c was an arbitrary linear extension of R , by Definition 11, P occurs in R . \square

In the following two simple lemmas, which follow from the definitions, P , Q , and R are patterns and I is an instance.

Lemma 2.3. *If P occurs in Q and P does not occur in I , then Q does not occur in I , i.e. $CSP_{\overline{SP}}(P) \subseteq CSP_{\overline{SP}}(Q)$.*

Lemma 2.4. *For any pattern P , $unordered(P)$ occurs in P .*

2.3. AC solvability. Arc consistency (AC) is a fundamental concept for CSPs.

Definition 12 . *Let $I = \langle X, D, A, \text{cpt} \rangle$ be a CSP instance. A point $\langle x, a \rangle \in A$ is called arc consistent if, for all variables $y \neq x$ in X there is some point $\langle y, b \rangle \in A$ compatible with $\langle x, a \rangle$.*

The CSP instance $\langle X, D, A, \text{cpt} \rangle$ is called arc consistent if $A \neq \emptyset$ and every point in A is arc consistent.

Points that are not arc-consistent cannot be part of a solution so can safely be removed. There are optimal $O(cd^2)$ algorithms for establishing arc consistency which repeatedly remove such points [4], where c is the number of non-trivial constraints and d the maximum domain size. Algorithms establishing arc consistency are implemented in all constraint solvers.

AC is a *decision procedure* for a class of CSP instances if for every instance from the class, after establishing arc consistency, non-empty domains for all variables guarantee the existence of a solution to the instance. (Note that a solution can then be found without backtrack by maintaining AC during search).

Definition 13 . *A pattern P is called AC-solvable if AC is a decision procedure for $CSP_{\overline{SP}}(P)$.*

The following lemma is a straightforward consequence of the definitions.

Lemma 2.5. *A pattern P is not AC-solvable if and only if there is an instance $I \in CSP_{\overline{SP}}(P)$ that is arc consistent and has no solution.*

The following lemma follows directly from Lemmas 2.3 and 2.5.

Lemma 2.6. *If P occurs in Q and P is not AC-solvable, then Q is not AC-solvable.*

As our main result we will, in Theorem 5.5, characterise all simple patterns that are AC-solvable.

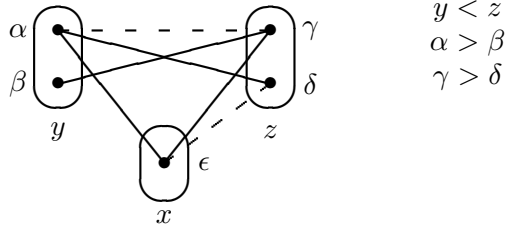


Figure 5: The ordered pattern EMC (Extended Max-Closed)

2.4. Pattern symmetry and equivalence. For an ordered pattern P , we denote by $\text{invDom}(P)$, $\text{invVar}(P)$ the patterns obtained from P by inverting the domain order or the variable order, respectively.

Lemma 2.7. *If P is not AC-solvable, then neither is any of $\text{invDom}(P)$, $\text{invVar}(P)$ or $\text{invDom}(\text{invVar}(P))$.*

Proof. For an arc-consistent instance the property of having a solution is independent of any variable or domain orderings. The claims follow from inverting the respective orders in the instance I of Lemma 2.5 proving that P is not AC-solvable. \square

Some patterns define the same classes of CSP instances.

Definition 14 . *Patterns P and P' are equivalent if*

$$\text{CSP}_{\overline{SP}}(P) = \text{CSP}_{\overline{SP}}(P').$$

Lemma 2.8. *If P occurs in P' and P' occurs in P , then P, P' are equivalent.*

Example 8 . *Let $LX^<$ be the pattern obtained from LX (Figure 13 on page 16) by adding the partial variable order $y < z$. Due to the symmetry of LX , observe that LX and $LX^<$ are equivalent.*

Example 9 . *The two patterns shown in Figure 4 on page 8 are also equivalent: (a) BTP^{do} with structure $x, y < z$ and $c < d$, and (b) BTP^{vo} with variable order $x < y < z$. We will call these the variable-ordered and domain-ordered versions of BTP , respectively, when it is necessary to make the distinction between the two. BTP (Figure 1(a) on page 5) will refer to the same pattern with the only structure $x, y < z$ which again, by symmetry, is equivalent to both BTP^{do} and BTP^{vo} .*

3. NEW TRACTABLE CLASSES SOLVED BY ARC CONSISTENCY

Our search for a characterisation of all simple patterns decided by arc consistency surprisingly uncovered four new tractable patterns, which we describe in this section. The first pattern we study is shown in Figure 5. It is a proper generalisation of the MC pattern (Figure 1(b) on page 5) since it has an extra variable and three extra edges.

Theorem 3.1. *AC is a decision procedure for $\text{CSP}_{\overline{SP}}(\text{EMC})$ where EMC is the pattern shown in Figure 5.*

Proof. Since establishing arc consistency only eliminates domain elements, and hence cannot introduce the pattern, it suffices to show that every arc-consistent instance $I = \langle X, D, A, \text{cpt} \rangle \in \text{CSP}_{\overline{SP}}(EMC)$ has a solution. We give a constructive proof. For a given domain ordering, let $x_1 < \dots < x_n$ be an ordering of X such that EMC does not occur in I . Define an assignment $\langle a_1, \dots, a_n \rangle$ to the variables $\langle x_1, \dots, x_n \rangle$ recursively as follows: $a_1 = \max(D(x_1))$ and, for $i > 1$,

$$a_i = \min\{a_i^j \mid 1 \leq j < i\}, \quad \text{where} \quad a_i^j = \max\{a \in D(x_i) \mid (a_j, a) \in R_{ji}\} \quad (3.1)$$

In other words, given an assignment $\langle a_1, \dots, a_{i-1} \rangle$ to variables $\langle x_1, \dots, x_{i-1} \rangle$, for $1 \leq j < i$, a_i^j is the maximum value in $D(x_i)$ compatible with a_j . Then a_i is the minimum of these values a_i^1, \dots, a_i^{i-1} . We prove by strong induction on n the following claim.

$C(n)$: $\langle a_1, \dots, a_n \rangle$ defined by Equation (3.1) is a solution to arc-consistent instances $I \in \text{CSP}_{\overline{SP}}(EMC)$ of size n .

The claim trivially holds for $n = 1$ since $a_1 \in D(x_1)$. It remains to show that if the claim holds for instances of size less than n then it holds for instances of size n .

We suppose that $C(1) \wedge \dots \wedge C(n-1)$ holds and we will show that this implies $C(n)$, i.e. that $\langle a_1, \dots, a_n \rangle$ is a solution to instance $I \in \text{CSP}_{\overline{SP}}(EMC)$ of size n . Suppose, for a contradiction, that $(a_j, a_k) \notin R_{jk}$ for some $1 \leq j < k \leq n$. If there is more than one such pair (j, k) , then choose k to be minimal and then for this value of k choose j to be minimal.

For $i > 1$, we denote by $\text{pred}(i)$ a value of $j < i$ such that $a_i = a_i^j$. Arc consistency guarantees that a_i^j exists and hence that a_i and $\text{pred}(i)$ are well defined. Let $m_0 = k$ and $m_r = \text{pred}(m_{r-1})$ for $r \geq 1$ if $m_{r-1} > 1$. Let t be such that $m_t = 1$. By definition of pred , we have

$$1 = m_t < m_{t-1} < \dots < m_1 < m_0 = k$$

which implies that this series is finite and hence that t is well-defined. We will show that for $r = 1, \dots, t$, $\exists b_r \in D(x_{m_r})$ such that $b_r > a_{m_r}$, which for $r = t$ will provides us with the contradiction we are looking for since $a_{m_t} = a_1 = \max(D(x_1))$.

We distinguish two cases: (1) $j > m_1$, and (2) $j < m_1$. Since $(a_j, a_k) \notin R_{jk}$ and $(a_{m_1}, a_k) \in R_{jk}$ we know that $j \neq m_1$.

Case (1) $j > m_1$: Define $b_0 = a_k^j$. By definition of a_k , we know that $a_k \leq a_k^j$. Since $(a_j, a_k) \notin R_{jk}$ and $(a_j, a_k^j) \in R_{jk}$, we have $b_0 = a_k^j > a_k$.

By our choice of j to be minimal, and since $j > m_1$ we know that $(a_{m_r}, a_k) \in R_{m_r k}$ for $r = 1, \dots, t$. Indeed, by minimality of k , we already had $(a_{m_r}, a_{m_s}) \in R_{m_r m_s}$ for $1 \leq s \leq r \leq t$. Thus, since $k = m_0$, we have

$$(a_{m_r}, a_{m_s}) \in R_{m_r m_s} \quad \text{for} \quad 0 \leq s \leq r \leq t. \quad (3.2)$$

By arc consistency, $\exists b_1 \in D(x_{m_1})$ such that $(b_1, b_0) \in R_{m_1 k}$. We have $(a_{m_1}, a_j) \in R_{m_1 j}$ by minimality of k and since $m_1, j < k$. Since $m_1 = \text{pred}(k)$ and hence $a_k = a_k^{m_1}$, we have $(a_{m_1}, a_k) \in R_{m_1 k}$ and $(a_{m_1}, b_0) \notin R_{m_1 k}$ by the maximality of $a_k^{m_1}$ in Equation (3.1) and since $b_0 > a_k = a_k^{m_1}$. We thus have the situation illustrated in Figure 6 for $h = 1$. Since the pattern EMC does not occur in I , we must have $b_1 > a_{m_1}$.

For $1 \leq r \leq t$, let H_r be the following hypothesis.

H_r : $\exists s(r) \in \{0, \dots, r-1\}$, $\exists p(r) < k$, $\exists b_r \in D(x_{m_r})$, with $b_r > a_{m_r}$, such that we have the situation shown in Figure 7.

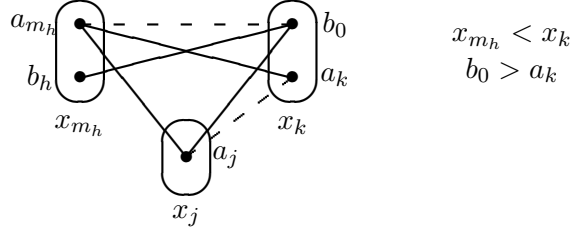


Figure 6: To avoid the pattern EMC, we must have $b_h > a_{m_h}$.

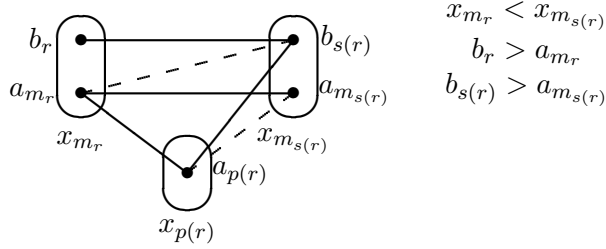


Figure 7: The situation corresponding to hypothesis H_r .

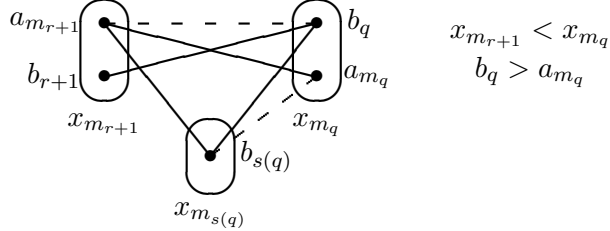


Figure 8: To avoid the pattern EMC, we must have $b_{r+1} > a_{m_{r+1}}$.

We have just shown that H_1 holds (with $s(1) = 0$ and $p(1) = j$). We now show, for $1 \leq r < t$, that $(H_1 \wedge \dots \wedge H_r) \Rightarrow H_{r+1}$.

We know that $(a_{m_{r+1}}, a_{m_r}) \in R_{m_{r+1}m_r}$ and $(a_{m_{r+1}}, b_r) \notin R_{m_{r+1}m_r}$, since $m_{r+1} = \text{pred}(m_r)$ and by maximality of $a_{m_r} = a_{m_r}^{m_{r+1}}$ in Equation (3.1). Let $q \in \{0, \dots, r\}$ be minimal such that $(a_{m_{r+1}}, b_q) \notin R_{m_{r+1}m_q}$. We distinguish two cases: (a) $q = 0$, and (b) $q > 0$.

If $q = 0$, then we have $(a_{m_{r+1}}, a_k) \in R_{m_{r+1}k}$ (from Equation (3.2), since $k = m_0$), $(a_{m_{r+1}}, b_0) \notin R_{m_{r+1}k}$ (since $q = 0$), $(a_{m_{r+1}}, a_j) \in R_{m_{r+1}j}$ (by minimality of k , since $m_{r+1}, j < k$). By arc consistency, $\exists b_{r+1} \in D(x_{m_{r+1}})$ such that $(b_{r+1}, b_0) \in R_{m_{r+1}k}$. We then have the situation illustrated in Figure 6 for $h = r + 1$. As above, from the absence of pattern EMC, we can deduce that $b_{r+1} > a_{m_{r+1}}$. We thus have H_{r+1} (with $s(r+1) = 0$ and $p(r+1) = j$).

If $q > 0$, then $H_1 \wedge \dots \wedge H_r$ implies that H_q holds. By minimality of q , we know that $(a_{m_{r+1}}, b_{s(q)}) \in R_{m_{r+1}m_{s(q)}}$ since $s(q) < q$. We know that $(a_{m_{r+1}}, a_{m_q}) \in R_{m_{r+1}m_q}$ from Equation (3.2), and that $(a_{m_{r+1}}, b_q) \notin R_{m_{r+1}m_q}$ by definition of q . We know that $(b_q, b_{s(q)}) \in R_{m_qm_{s(q)}}$ and $(a_{m_q}, b_{s(q)}) \notin R_{m_qm_{s(q)}}$ from H_q . By arc consistency, $\exists b_{r+1} \in D(x_{m_{r+1}})$ such

that $(b_{r+1}, b_q) \in R_{m_{r+1}m_q}$. We then have the situation illustrated in Figure 8. As above, from the absence of pattern EMC, we can deduce that $b_{r+1} > a_{m_{r+1}}$. We thus have H_{r+1} (with $s(r+1) = q$ and $p(r+1) = s(q)$).

Case (2) $j < m_1$: Consider the subproblem I' of I on variables $\{x_1, x_2, \dots, x_{m_1-1}\} \cup \{x_k\}$. Since x_{m_1} does not belong to the set of variables of I' , this instance has size strictly less than n , and hence has a solution by our inductive hypothesis $C(1) \wedge \dots \wedge C(n-1)$ (i.e. that a solution is given by Equation (3.1) for arc-consistent instances in $\text{CSP}_{\overline{SP}}(\text{EMC})$ of size less than n). The values of a_i may differ between I and I' . However, we can see from its definition given in Equation (3.1), that the value of a_i depends uniquely on the subproblem on previous variables $\{x_1, \dots, x_{i-1}\}$. Showing the dependence on the instance by a superscript, we thus have $a_i^{I'} = a_i^I$ ($i = 1, \dots, m_1 - 1$) although $a_k^{I'}$ may (and, in fact, does) differ from a_k^I . By our inductive hypothesis $C(1) \wedge \dots \wedge C(n-1)$, $\langle a_1, \dots, a_{m_1-1}, a_k^{I'} \rangle$ is a solution to I' . Setting $b_0 = a_k^{I'}$, it follows that $(a_i, b_0) \in R_{ik}$ for $1 \leq i < m_1$. In particular, since $j < m_1$, we have $(a_j, b_0) \in R_{jk}$. Now $a_k^I \leq a_k^{I'} = b_0$, since I' is a subinstance of I (and so, from Equation (3.1), a_k^I is the minimum of a superset over which $a_k^{I'}$ is a minimum). Thus $a_k = a_k^I < b_0$, since $(a_j, b_0) \in R_{jk}$ and $(a_j, a_k) \notin R_{jk}$.

By arc consistency, $\exists b_1 \in D(x_{m_1})$ such that $(b_1, b_0) \in R_{m_1k}$. As in case (1), we have the situation illustrated in Figure 6 on page 12 for $h = 1$. Since the pattern EMC does not occur in I , we must have $b_1 > a_{m_1}$.

Consider the hypothesis H_r stated in case (1) and illustrated in Figure 7 on page 12. We have just shown that H_1 holds (with $s(1) = 0$ and $p(1) = j$). We now show, for $1 \leq r < t$, that $(H_1 \wedge \dots \wedge H_r) \Rightarrow H_{r+1}$.

As in case (1), we know that $(a_{m_{r+1}}, a_{m_r}) \in R_{m_{r+1}m_r}$ and $(a_{m_{r+1}}, b_r) \notin R_{m_{r+1}m_r}$. Let $q \in \{0, \dots, r\}$ be minimal such that $(a_{m_{r+1}}, b_q) \notin R_{m_{r+1}m_q}$. We have seen above that $(a_{m_{r+1}}, b_0) \in R_{m_{r+1}k}$ (since $x_{m_{r+1}}, x_{m_0}$ are assigned, respectively, the values $a_{m_{r+1}}, b_0$ in a solution to I'). Therefore, we can deduce that $q > 0$. Therefore $H_1 \wedge \dots \wedge H_r$ implies that H_q holds. By minimality of k , and since $m_q < m_0 = k$, we know that $(a_{m_{r+1}}, a_{m_q}) \in R_{m_{r+1}m_q}$. As in case (1), by minimality of q , we know that $(a_{m_{r+1}}, b_{s(q)}) \in R_{m_{r+1}m_{s(q)}}$. By arc consistency, $\exists b_{r+1} \in D(x_{m_{r+1}})$ such that $(b_{r+1}, b_q) \in R_{m_{r+1}m_q}$. We thus have the situation illustrated in Figure 8 on page 12. Again, from the absence of pattern EMC, we can deduce that $b_{r+1} > a_{m_{r+1}}$. We thus again have H_{r+1} with $s(r+1) = q$ and $p(r+1) = s(q)$.

Thus, by induction on r , we have shown in both cases that H_t holds. But recall that $m_t = 1$ and that a_1 was chosen to be the maximal element of $D(x_1)$ and hence $\nexists b_t \in D(x_1)$ such that $b_t > a_1$. This contradiction shows that $\langle a_1, \dots, a_n \rangle$ is a solution, as claimed. \square

The next two patterns we study in this section, shown in Figure 9 and Figure 10, are similar to EMC but the three patterns are incomparable (in the sense that none occurs in another) due to the different orders on the three variables.

Theorem 3.2. *AC is a decision procedure for $\text{CSP}_{\overline{SP}}(\text{BTX})$ where BTX is the pattern shown in Figure 9.*

Proof. Since establishing arc consistency only eliminates domain elements, and hence cannot introduce the pattern, we only need to show that every arc-consistent instance $I = \langle X, D, A, \text{cpt} \rangle \in \text{CSP}_{\overline{SP}}(\text{BTX})$ has a solution. For a given domain ordering, let $x_1 < \dots < x_n$ be an ordering of X such that BTX does not occur in I . In fact we will show a stronger result by proving that the hypothesis H_n , below, holds for all $n \geq 1$.

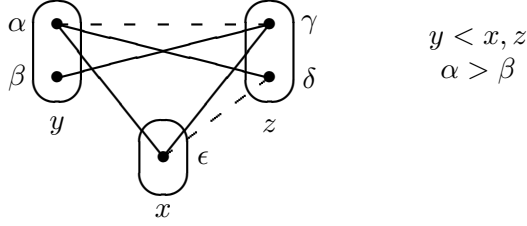


Figure 9: The ordered pattern BTX.

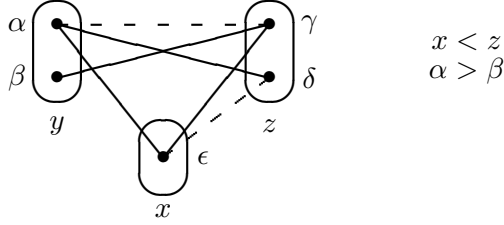


Figure 10: The ordered pattern BTI.

H_n : for all arc-consistent instances $I = \langle X, D, A, \text{cpt} \rangle$ from $\text{CSP}_{\overline{SP}}(BTX)$ with $|X| = n$, if $a = \max(D(x_1))$, then I has a solution s with $s(x_1) = a$.

Trivially, H_1 holds. Suppose that H_{n-1} holds where $n > 1$. We will show that this implies H_n , which will complete the proof by induction. Let $D'(x_i) = \{b \in D(x_i) \mid (a, b) \in R_{1i}\}$ ($i = 2, \dots, n$). Denote by I' the subproblem of I on variables $2, \dots, n$ and domains $D'(x_i)$ ($i = 2, \dots, n$). To complete the inductive proof, it is sufficient to show that I' is arc consistent: since $I' \in \text{CSP}_{\overline{SP}}(BTX)$ and has $n - 1$ variables, by H_{n-1} , if I' is arc consistent it has a solution which can clearly be extended to a solution to I by adding the assignment (x_1, a) .

To show arc consistency of I' , consider any variable x_i with $i > 1$ and any $b \in D'(x_i)$. (We know by arc consistency of I that $D'(x_i)$ is non-empty; i.e. $(a, b) \in R_{1i}$.) Now let x_j be any other variable with $j > 1$. To complete the proof, it suffices to show that b has a support in $D'(x_j)$.

By arc consistency of I , we can deduce the existence of $c \in D(x_j)$ such that $(b, c) \in R_{ij}$, and then $a' \in D(x_1)$ such that $(a', c) \in R_{1j}$, as well as $d \in D(x_j)$ such that $(a, d) \in R_{1j}$ (i.e. $d \in D'(x_j)$). If b has no support in $D'(x_j)$, then we must have $c \notin D'(x_j)$ (i.e. $(a, c) \notin R_{1j}$) and $(b, d) \notin R_{ij}$. Since a is the maximum element of $D(x_1)$, we know that $a' \leq a$. Indeed, since $(a, c) \notin R_{1j}$ and $(a', c) \in R_{1j}$, we have that $a' < a$. But then the pattern BTX occurs in I , as shown in Figure 11. This contradiction shows that b does have a support in $D'(x_j)$ and hence that I' is arc consistent, as required. \square

Theorem 3.3. *AC is a decision procedure for $\text{CSP}_{\overline{SP}}(BTI)$ where BTI is the pattern shown in Figure 10.*

Proof. Since establishing arc consistency only eliminates domain elements, and hence cannot introduce the pattern, we only need to show that every arc-consistent instance $I = \langle X, D, A, \text{cpt} \rangle \in \text{CSP}_{\overline{SP}}(BTI)$ has a solution. Let $x_1 < \dots < x_n$ be an ordering of

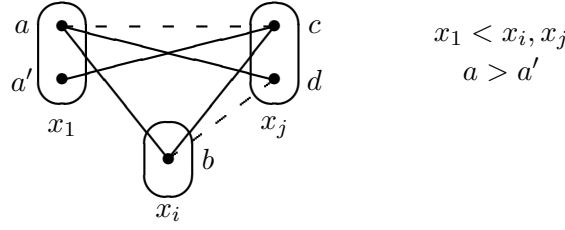


Figure 11: An occurrence of the pattern BTX.

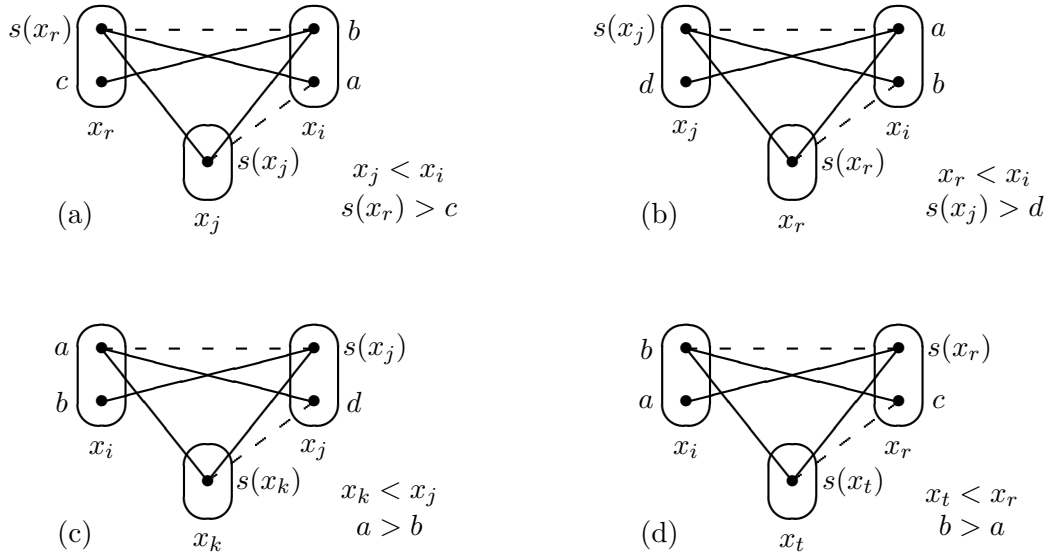


Figure 12: Occurrences of the pattern BTI.

X such that BTI does not occur in I . In fact, we will show a stronger result by proving that, for all arc-consistent instances $I = \langle X, D, A, \text{cpt} \rangle \in \text{CSP}_{\overline{\text{SP}}}(BTI)$, I has a solution s defined recursively by: $s(x_i)$ is the maximum value in $D(x_i)$ compatible with all previous assignments $s(x_1), \dots, s(x_{i-1})$.

Let T_i denote the set of values in $D(x_i)$ compatible with the assignments $s(x_1), \dots, s(x_{i-1})$ (defined recursively as above). If each T_i ($i = 1, \dots, n$) is non-empty, then $s(x_1), \dots, s(x_n)$ is a solution to I . Let I_i denote the subinstance of I on the first i variables x_1, \dots, x_i . $T_1 = D(x_1)$ and is non-empty since I is arc consistent, and hence $s(x_1) = \max(T_1)$ is a solution to I_1 . Suppose that $s(x_1), \dots, s(x_{i-1})$, as defined above, is a solution to I_{i-1} . We will show that $s(x_i)$ exists and hence that $s(x_1), \dots, s(x_i)$ is a solution to I_i , which by a simple induction will complete the proof. Suppose for a contradiction that $s(x_i)$ does not exist, i.e. that $T_i = \emptyset$.

For all u , let $R_{ji}(u)$ denote the subset of $D(x_i)$ which is compatible with the assignment of u to x_j , i.e. $R_{ji}(u) = \{v \in D(x_i) \mid (u, v) \in R_{ji}\}$. For $j \in \{1, \dots, i-1\}$, let T_i^j be the intersection of the sets $R_{hi}(s(x_h))$ ($h = 1, \dots, j$). By our hypothesis that $T_i = \emptyset$, we know that $T_i^{i-1} = T_i = \emptyset$. By arc consistency, $T_i^1 \neq \emptyset$. Let $j \in \{2, \dots, i-1\}$ be minimal such that

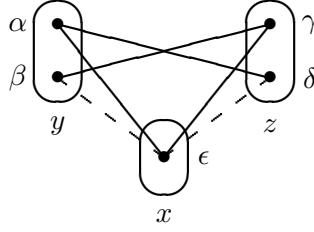


Figure 13: The pattern LX.

$T_i^j = \emptyset$. Thus

$$R_{ji}(s(x_j)) \cap T_i^{j-1} = \emptyset \quad (3.3)$$

By arc consistency, $\exists b \in D(x_i)$ such that $(s(x_j), b) \in R_{ji}$ (i.e. $b \in R_{ji}(s(x_j))$). By Equation (3.3) and definition of T_i^{j-1} , there is some $r < j$ such that $(s(x_r), b) \notin R_{ri}$. Choose r to be minimal. Consider $a \in T_i^{j-1}$ (which is non-empty since j was chosen to be minimal). Then $(s(x_r), a) \in R_{ri}$, by definition of T_i^{j-1} , since $r \leq j-1$. But $(s(x_j), a) \notin R_{ji}$ by (3.3). By arc consistency, $\exists c \in D_r$ such that $(c, b) \in R_{ri}$ and $\exists d \in D(x_j)$ such that $(d, a) \in R_{ji}$. By our inductive hypothesis that $s(x_1), \dots, s(x_{i-1})$ is a solution to I_{i-1} , we know that $(s(x_r), s(x_j)) \in R_{rj}$ since $r, j < i$. Because of their different compatibilities with, respectively, b and a , we know that $c \neq s(x_r)$ and $d \neq s(x_j)$. If $c < s(x_r)$, then, since $r < i$, the pattern BTI occurs in I , as shown in Figure 12(a) on page 15; so we can deduce that $c > s(x_r)$. Similarly, if $d < s(x_j)$, then, since $j < i$, the pattern BTI occurs in I , as shown in Figure 12(b) on page 15; so we can deduce that $d > s(x_j)$.

But, by definition of s , $s(x_r)$ is the maximal element of T_r . So, since $c > s(x_r)$, there must be some $t < r$ such that $(s(x_t), c) \notin R_{tr}$. By minimality of r , we know that $(s(x_t), b) \in R_{ti}$. Similarly, there must be some $k < j$ such that $(s(x_k), d) \notin R_{kj}$ since $d > s(x_j)$ and $s(x_j)$ is the maximal element of T_j . Since $a \in T_i^{j-1}$ and $k < j$, we know that $(s(x_k), a) \in R_{ki}$. By our inductive hypothesis that $s(x_1), \dots, s(x_{i-1})$ is a solution to I_{i-1} , we know that $(s(x_k), s(x_j)) \in R_{kj}$ and $(s(x_t), s(x_r)) \in R_{tr}$ since $k, j, t, r < i$. We know that $a \neq b$ because they have different compatibilities with $s(x_j)$. If $a > b$, then, since $k < j$, the pattern BTI occurs in I , as shown in Figure 12(c) on page 15. And, if $b > a$, then the pattern BTI occurs in I , as shown in Figure 12(d) on page 15. This contradiction shows that $T_i \neq \emptyset$ (for each $i = 1, \dots, n$) and hence that I has a solution s . \square

We conclude this section with a pattern which is essentially different from the patterns EMC, BTX, and BTI, since it includes two negative edges that meet but has no domain or variable order. The tractability of this pattern was previously unknown [24].

Theorem 3.4. *AC is a decision procedure for $\text{CSP}_{\overline{SP}}(LX)$ where LX is the pattern shown in Figure 13.*

Proof. Since establishing arc consistency only eliminates domain elements, and hence cannot introduce the pattern, we only need to show that every arc-consistent instance $I \in \text{CSP}_{\overline{SP}}(LX)$ has a solution. In fact we will show a stronger result by proving that the hypothesis H_n , below, holds for all $n \geq 1$.

H_n : for all arc-consistent instances $I = \langle X, D, A, \text{cpt} \rangle \in \text{CSP}_{\overline{SP}}(LX)$ with $|X| = n$, $\forall x_i \in X$, $\forall a \in D(x_i)$, I has a solution s such that $s(x_i) = a$.

Trivially, H_1 holds. Suppose that H_{n-1} holds where $n > 1$. We will show that this implies H_n , which will complete the proof by induction.

Consider an arc-consistent instance $I = \langle X, D, A, \text{cpt} \rangle$ from $\text{CSP}_{\overline{SP}}(LX)$ with $X = \{x_1, \dots, x_n\}$ and let $a \in D(x_i)$ where $1 \leq i \leq n$. Let I_{n-1} denote the subproblem of I on variables $X \setminus \{x_i\}$. For any solution s of I_{n-1} , we denote by $CV(\langle x_i, a \rangle, s)$ the set of variables in $X \setminus \{x_i\}$ on which s is compatible with the unary assignment $\langle x_i, a \rangle$, i.e.

$$CV(\langle x_i, a \rangle, s) = \{x_j \in X \setminus \{x_i\} \mid (a, s(x_j)) \in R_{ij}\}$$

Consider two distinct solutions s, s' to I_{n-1} . If we have $x_j \in CV(\langle x_i, a \rangle, s) \setminus CV(\langle x_i, a \rangle, s')$ and $x_k \in CV(\langle x_i, a \rangle, s') \setminus CV(\langle x_i, a \rangle, s)$, then the pattern LX occurs in I under the mapping $x \mapsto x_i, y \mapsto x_j, z \mapsto x_k, \alpha \mapsto s(x_j), \beta \mapsto s'(x_j), \gamma \mapsto s'(x_k), \delta \mapsto s(x_k), \epsilon \mapsto a$ (see Figure 13 on page 16). Since LX does not occur in I , we can deduce that the sets $CV(\langle x_i, a \rangle, s)$, as s varies over all solutions to I_{n-1} , form a nested family of sets. Let s_a be a solution to I_{n-1} such that $CV(\langle x_i, a \rangle, s_a)$ is maximal for inclusion.

Consider any $x_j \in X \setminus \{x_i\}$. By arc consistency, $\exists b \in D(x_j)$ such that $(a, b) \in R_{ij}$. By our inductive hypothesis H_{n-1} , there is a solution s to I_{n-1} such that $s(x_j) = b$. Since $(a, s(x_j)) = (a, b) \in R_{ij}$, we have $x_j \in CV(\langle x_i, a \rangle, s)$. By maximality of s_a , this implies $x_j \in CV(\langle x_i, a \rangle, s_a)$, i.e. $(a, s_a(x_j)) \in R_{ij}$. Since this is true for any $x_j \in X \setminus \{x_i\}$, we can deduce that s_a can be extended to a solution to I (which assigns a to x_i) by simply adding the assignment $\langle x_i, a \rangle$ to s_a . \square

The proof of Theorem 3.4 shows that to find a solution to arc-consistent instances in $\text{CSP}_{\overline{SP}}(LX)$, it suffices to maintain arc consistency during search (a standard algorithm in CSP solvers) making arbitrary choices of values to assign to each variable: search will always be backtrack-free.

4. RECOGNITION PROBLEM FOR UNKNOWN ORDERS

One possible way of applying our new tractable classes is the automatic recognition by a general-purpose CSP solver that an instance (or a sub-instance encountered during search after instantiation of a subset of variables) belongs to one of our tractable classes. In this section we study the complexity of this recognition problem.

For an unordered pattern P of size k , checking for (the non-occurrence of) P in a CSP instance I is solvable in time $O(|I|^k)$ by simple exhaustive search. Consequently, checking for (the non-occurrence of) unordered patterns of constant size is solvable in polynomial time. However, the situation is less obvious for ordered patterns since we have to test all possible orderings of I .

The following result was shown in [16].

Theorem 4.1. *Given a binary CSP instance I with a fixed total order on the domain, there is a polynomial-time algorithm to find a total variable ordering such that BTP does not occur in I (or to determine that no such ordering exists).*

We show that the same result holds for the other three ordered patterns studied in this paper, namely BTI, BTX, and EMC.

Theorem 4.2. *Given a binary CSP instance I with a fixed total order on the domain and a pattern $P \in \{\text{BTI}, \text{BTX}, \text{EMC}\}$, there is a polynomial-time algorithm to find a total variable ordering such that P does not occur in I (or to determine that no such ordering exists).*

Proof. We give a proof only for BTX as the same idea works for the other two patterns as well. Given a binary CSP instance I with n variables x_1, \dots, x_n , we define an associated CSP instance Π_I that has a solution precisely when there exists a suitable variable ordering for I . To construct Π_I , let O_1, \dots, O_n be variables taking values in $\{1, \dots, n\}$ representing positions in the ordering. We impose the ternary constraint $O_i > \min(O_j, O_k)$ for all triples of variables x_i, x_j, x_k in I such that the BTX pattern occurs for some $\alpha, \beta \in D(x_i)$ with $\alpha > \beta$, $\epsilon \in D(x_j)$, and $\gamma, \delta \in D(x_k)$ when the variables are ordered $x_i < x_j, x_k$. The instance Π_I has a solution precisely if there is an ordering of the variables x_1, \dots, x_n of I for which BTX does not occur. Note that if the solution obtained represents a partial order (i.e. if O_i and O_j are assigned the same value for some $i \neq j$), then it can be extended to a total order which still satisfies all the constraints by arbitrarily choosing the order of those O_i 's that are assigned the same value. This reduction is polynomial in the size of I . We now show that all constraints in Π_I are ternary min-closed and thus Π_I can be solved in polynomial time [30]. Let $\langle p_1, q_1, r_1 \rangle$ and $\langle p_2, q_2, r_2 \rangle$ satisfy any constraint in Π_I . Then $p_1 > \min(q_1, r_1)$ and $p_2 > \min(q_2, r_2)$, and thus $\min(p_1, p_2) > \min(\min(q_1, r_1), \min(q_2, r_2)) = \min(\min(q_1, q_2), \min(r_1, r_2))$. Consequently, $\langle \min(p_1, p_2), \min(q_1, q_2), \min(r_1, r_2) \rangle$ also satisfies the constraint. We can deduce that all constraints in Π_I are min-closed. \square

Using the same technique, we can also show the following.

Theorem 4.3. *Given a binary CSP instance I with a fixed total variable order and a pattern $P \in \{BTI, BTX\}$, there is a polynomial-time algorithm to find a total domain ordering such that P does not occur in I (or determine that no such ordering exists).*

It is known that determining a domain order for which MC does not occur is NP-hard [27]. Not surprisingly, for EMC when the domain order is not known, detection becomes NP-hard. For the case of BTX and BTI, if neither the domain nor variable order is known, finding orders for which the pattern does not occur is again NP-hard.

Theorem 4.4. *For the pattern EMC, even for a fixed total variable order of an arc-consistent binary CSP instance I , it is NP-hard to find a total domain ordering of I such that the pattern does not occur in I . For patterns BTX and BTI, it is NP-hard to find total variable and domain orderings of an arc-consistent binary CSP instance I such that the pattern does not occur in I .*

Proof. To show this, we exhibit a polynomial reduction from 3SAT. Given an n -variable instance I_{3SAT} of 3SAT with m clauses, we create a basic domain B of size $2n$ with a value a_i for each variable X_i in I_{3SAT} and another a_{n+i} for its negation $\overline{X_i}$. We construct a binary CSP instance I_{CSP} , such that the domain of each variable contains B , and such that there exists an appropriate order of B if and only if I_{3SAT} has a solution. For each total ordering $>$ of B there is a corresponding assignment to the variables of I_{3SAT} given by $X_i = \text{true}$ if and only if $a_i > a_{i+n}$. To complete the reduction we have to show how to impose a clause, e.g. $(a_i > a_{i+n}) \vee (a_j > a_{j+n}) \vee (a_k > a_{k+n})$. The basic construction of I_{CSP} is composed of the following elements: $N = 6m$ variables linked by the equality constraints $x_i = x_{i+1}$ ($i = 1, \dots, N - 1$).

Consider first the case of EMC. We assume the variable order given by $x_i < x_j$ iff $i < j$. To impose a clause we construct a gadget on three variables x_p, x_q, x_r of I_{CSP} which are not linked by any other constraints in our construction (in particular, not consecutive variables linked by equality constraints). To be specific, for the i th clause, we choose $p = 2i - 1$, $q = 4i - 1$ and $r = 6i - 1$. We add four extra values a_{\max}, b, c, d (of which b, c, d depend on

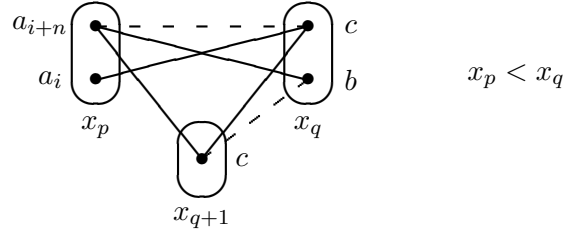


Figure 14: To avoid the pattern EMC, we must have $(a_i > a_{i+n})$ or $(b > c)$.

the clause) to the basic domain B of each of these three variables x_p, x_q, x_r . The domain size of each variable x_i in I_{CSP} is thus $2n + 4$. The value a_{\max} is compatible with all values in the domains of the other variables. This ensures arc consistency for all domain values, and if $a_{\max} > a$ for all domain values $a \neq a_{\max}$, then the pattern cannot occur on a_{\max} . We now specify the constraints between the variables x_p, x_q, x_r . We place negative edges between all pairs of values other than a_{\max} except for three positive edges in each constraint. In the constraint between x_p and x_q we add the three positive edges: (a_i, b) , (a_i, c) , (a_{i+n}, b) . If $a_{i+n} > a_i$ in $D(x_p)$ and $c > b$ in $D(x_q)$, then the pattern EMC occurs in I_{CSP} as shown in Figure 14. The third variable of the pattern is x_{q+1} which is linked by an equality constraint to x_q and by a trivial constraint to x_p . Thus, to avoid the pattern occurring in I_{CSP} the domain order must respect

$$(a_i > a_{i+n}) \vee (b > c)$$

By adding similar constraints between x_p, x_r and x_q, x_r , we can also impose

$$(a_j > a_{j+n}) \vee (c > d) \quad \text{and} \\ (a_k > a_{k+n}) \vee (d > b)$$

By imposing these three inequalities, we impose $(a_i > a_{i+n}) \vee (a_j > a_{j+n}) \vee (a_k > a_{k+n})$ (since we cannot simultaneously have $b > c > d > b$) which corresponds to the clause $X_i \vee X_j \vee X_k$ in I_{3SAT} . By inverting the roles of a_i and a_{i+n} we can clearly impose clauses involving negative literals. This completes the reduction from I_{3SAT} to the problem of finding a domain ordering of a binary CSP instance so that EMC does not occur. Since this reduction is clearly polynomial, we can conclude that the problem of testing the existence of a domain order so that EMC does not occur is NP-hard.

Now consider the case of the pattern BTX. We use a similar construction to the case of EMC, above. Again, to simulate a clause $X_i \vee X_j \vee X_k$ in I_{3SAT} we need to impose $(a_i > a_{i+n}) \vee (a_j > a_{j+n}) \vee (a_k > a_{k+n})$. This can be achieved by imposing:

$$(a_i > a_{i+n}) \vee (x_p > x_q), \\ (a_j > a_{j+n}) \vee (x_q > x_r) \quad \text{and} \\ (a_k > a_{k+n}) \vee (x_r > x_p)$$

For example, to impose $(a_i > a_{i+n}) \vee (x_p > x_q)$ we place the same gadget as above (i.e. positive edges (a_i, b) , (a_i, c) , (a_{i+n}, b)) on each of the three pairs of variables (x_p, x_q) , (x_{p+1}, x_q) and (x_{q+1}, x_p) . To avoid BTX on variables x_p, x_q, x_{q+1} , on variables x_{p+1}, x_q, x_{q+1}

and on variables x_{q+1}, x_p, x_{p+1} , we must have

$$\begin{aligned} & (a_i > a_{i+n}) \vee (x_p > x_q) \vee (x_p > x_{q+1}), \\ & (a_i > a_{i+n}) \vee (x_{p+1} > x_q) \vee (x_{p+1} > x_{q+1}) \quad \text{and} \\ & (a_i > a_{i+n}) \vee (x_{q+1} > x_p) \vee (x_{q+1} > x_{p+1}) \end{aligned}$$

Since there is a total strict ordering on the variables, this is logically equivalent to imposing $(a_i > a_{i+n}) \vee (x_p > x_q)$, as required (provided none of the variables $x_p, x_{p+1}, x_q, x_{q+1}$ are used in other gadgets), given our freedom to choose the positions of x_{p+1} and x_{q+1} in the order.

Finally, we consider the pattern BTI. But this is an easier case than BTX. We just need to place the gadget on (x_p, x_q) to impose $(a_i > a_{i+n}) \vee (x_p > x_q)$ to avoid the pattern BTI.

Thus, EMC is NP-hard to detect when the domain order of the instance is not fixed, and BTX, BTI are NP-hard to detect when neither the domain order nor the variable order of the instance is fixed. \square

The results from this section are summarised in Table 1. We use the star to denote uninteresting cases. Note that since LX is an unordered pattern the questions of determining variable and/or domain orders are not interesting. Similarly, since pattern BTP only orders variables the question of determining a domain order is not interesting. An important point is that for a fixed domain order (which is a natural assumption for numerical domain values, for example) we can effectively exhaust over all variable orders in polynomial time for all variable-ordered patterns studied in this paper (BTP, BTI, BTX, EMC).

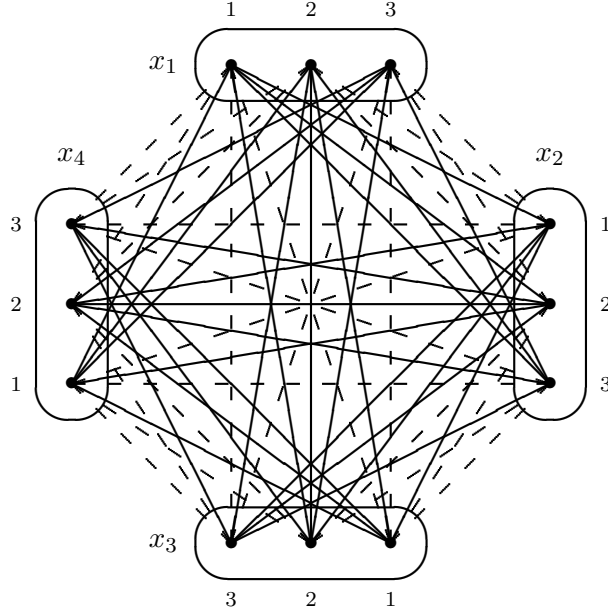
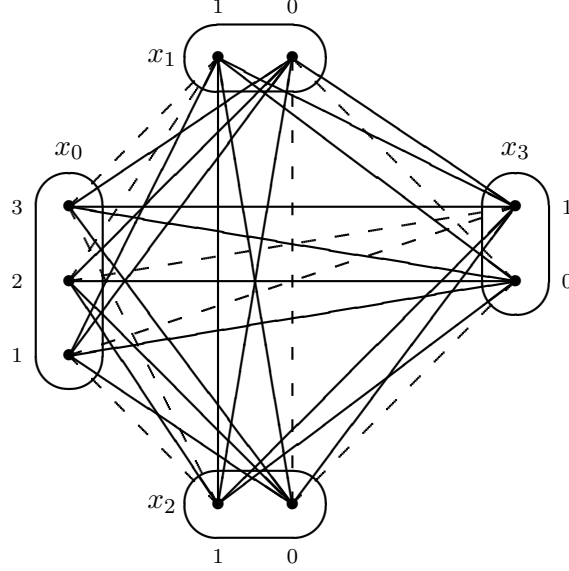
	BTP	BTI	BTX	EMC	LX
domain order given	P [Thm 4.1]	P [Thm 4.2]	P [Thm 4.2]	P [Thm 4.2]	*
variable order given	*	P [Thm 4.3]	P [Thm 4.3]	NP-h [Thm 4.4]	*
neither order given	P [Thm 4.1]	NP-h [Thm 4.4]	NP-h [Thm 4.4]	NP-h [Thm 4.4]	*

Table 1: Summary of the complexity (P or NP-hard) of the recognition problem for each of our patterns for the cases in which the domain order is given (but the variable order has to be determined), the variable order is given (but the domain order has to be determined), or neither order is given.

5. CHARACTERISATION OF PATTERNS SOLVED BY AC

5.1. Instances not solved by arc consistency. We first give a set of instances, each of which is arc consistent and has no solution. If for any of these instances I , we have $I \in \text{CSP}_{\overline{\text{SP}}}(P)$, then this constitutes a proof, by Lemma 2.5, that pattern P is not solved by arc consistency. For simplicity of presentation, in each of the following instances, we suppose the variable order given by $x_i < x_j$ if $i < j$.

- I_{K4} (shown in Figure 15) is composed of four variables with domains $D(x_i) = \{1, 2, 3\}$ ($i = 1, 2, 3, 4$), and the following constraints: $(x_i = 1) \vee (x_j = 3)$ ($(i, j) = (1, 2), (2, 3), (3, 4), (4, 1)$) and $(x_i = 2) \vee (x_j = 2)$ ($(i, j) = (1, 3), (2, 4)$).
- I_4 (shown in Figure 16) is composed of four variables with domains $D(x_0) = \{1, 2, 3\}$, $D(x_i) = \{0, 1\}$ ($i = 1, 2, 3$), and the following constraints: $x_i \vee x_j$ ($1 \leq i < j \leq 3$) and $(x_0 = i) \vee \overline{x_i}$ ($i = 1, 2, 3$).

Figure 15: The instance I_{K4} .Figure 16: The instance I_4 .

- $I_{2\Delta}^{SAT}$ (shown in Figure 17(a)) is composed of five Boolean variables and the following constraints: $x_1 \vee x_2$, $x_3 \vee x_4$, $\overline{x_1} \vee x_5$, $\overline{x_2} \vee x_5$, $\overline{x_3} \vee \overline{x_5}$, $\overline{x_4} \vee \overline{x_5}$.
- I_5 (shown in Figure 18) is composed of five variables with domains $D(w_i) = \{0, 1\}$ ($i = 1, 2, 3$), $D(x_i) = \{1, 2, 3\}$, and the constraints: $\overline{w_i} \vee (x_1 = i)$ ($i = 1, 2, 3$) and $w_i \vee (x_2 = i)$ ($i = 1, 2, 3$). In this instance the variable order is $w_1 < w_2 < w_3 < x_1 < x_2$.

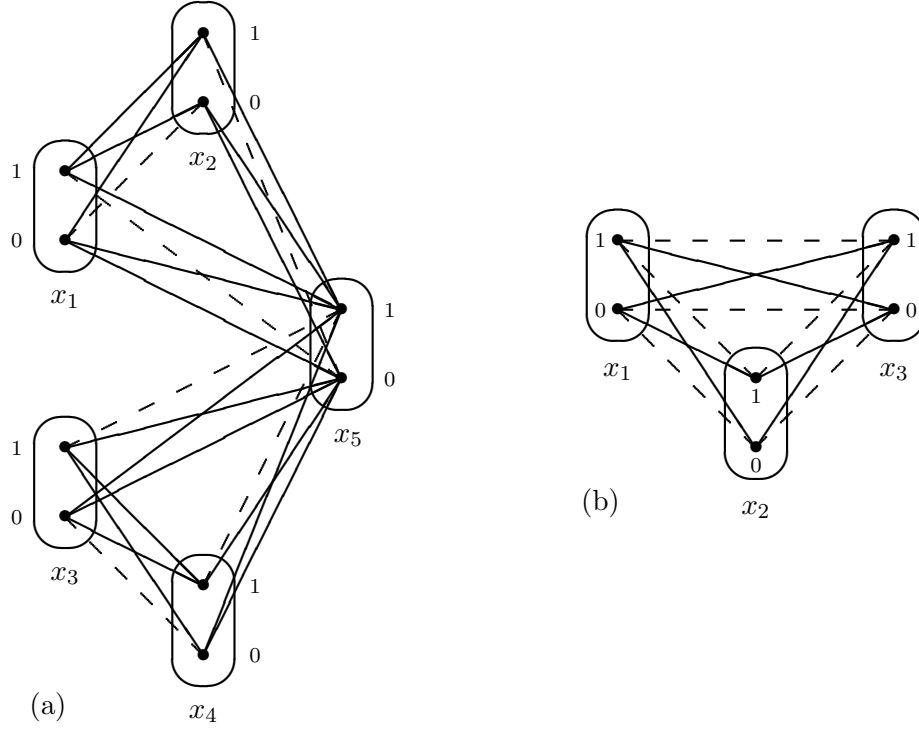


Figure 17: The instances (a) $I_{2\Delta}^{SAT}$ and (b) I_3^{2COL} .

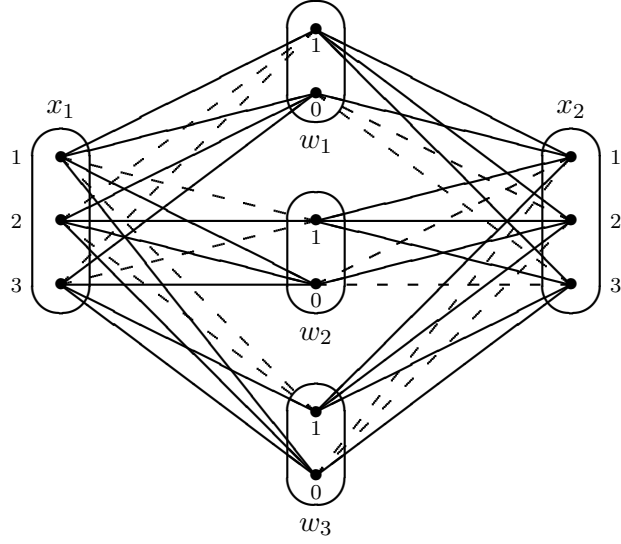
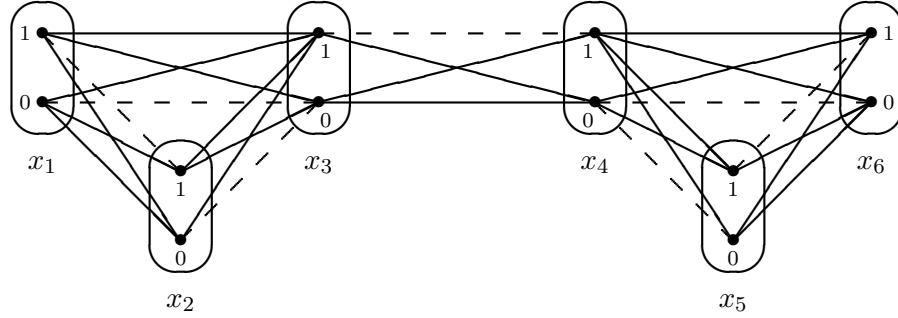
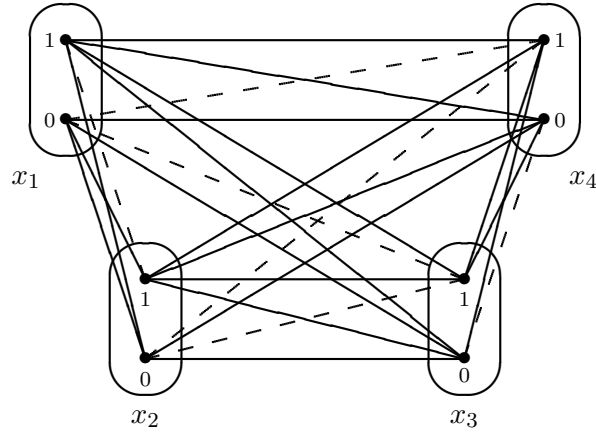


Figure 18: The instance I_5 (with variable order $w_1 < w_2 < w_3 < x_1 < x_2$).

- I_6^{SAT} (shown in Figure 19) is composed of six Boolean variables and the following constraints: $\overline{x_1} \vee \overline{x_2}$, $x_1 \vee x_3$, $x_2 \vee x_3$, $\overline{x_3} \vee \overline{x_4}$, $x_4 \vee x_5$, $x_4 \vee x_6$, $\overline{x_5} \vee \overline{x_6}$.

Figure 19: The instance I_6^{SAT} .Figure 20: The instance $I_{K^4}^{SAT}$.

- $I_{K^4}^{SAT}$ (shown in Figure 20) is composed of four Boolean variables and the following constraints: $\overline{x_1} \vee \overline{x_2}$, $x_3 \vee x_4$ and $x_i \vee \overline{x_j}$ (for $(i, j) = (1, 3), (1, 4), (2, 3), (2, 4)$).
- I_3^{COL} (shown in Figure 17(b)) is composed of three Boolean variables and the three inequality constraints: $x_i \neq x_j$ ($1 \leq i < j \leq 3$).

In figures representing CSP instances, similarly to patterns, ovals represent variables, the set of points inside an oval the elements of the variable's domain, a dashed (respectively, solid) line joining two points represents the incompatibility (respectively, compatibility) of the two points. In order not to clutter up figures representing instances, trivial constraints containing only positive edges (i.e. corresponding to complete relations) are not shown. Figure 21(a) is a pattern which does not occur in the instance I_{K^4} (Figure 15 on page 21). Similarly, Figure 21(b) is a pattern which does not occur in the instance I_4 (Figure 16 on page 21), and the pattern in Figure 21(c) does not occur in instance $I_{2\Delta}^{SAT}$. Figure 21(d), (e) and (f) are three patterns which do not occur in the instance I_5 (Figure 18 on page 22). The pattern (known as $T1$) shown in Figure 21(d) is, in fact, a tractable pattern [15], but the fact that it does not occur in I_5 (an arc-consistent instance which has no solution) shows that arc consistency is not a decision procedure for $\text{CSP}_{\overline{SP}}(T1)$. This instance was constructed using certain known properties of the pattern $T1$ [24].

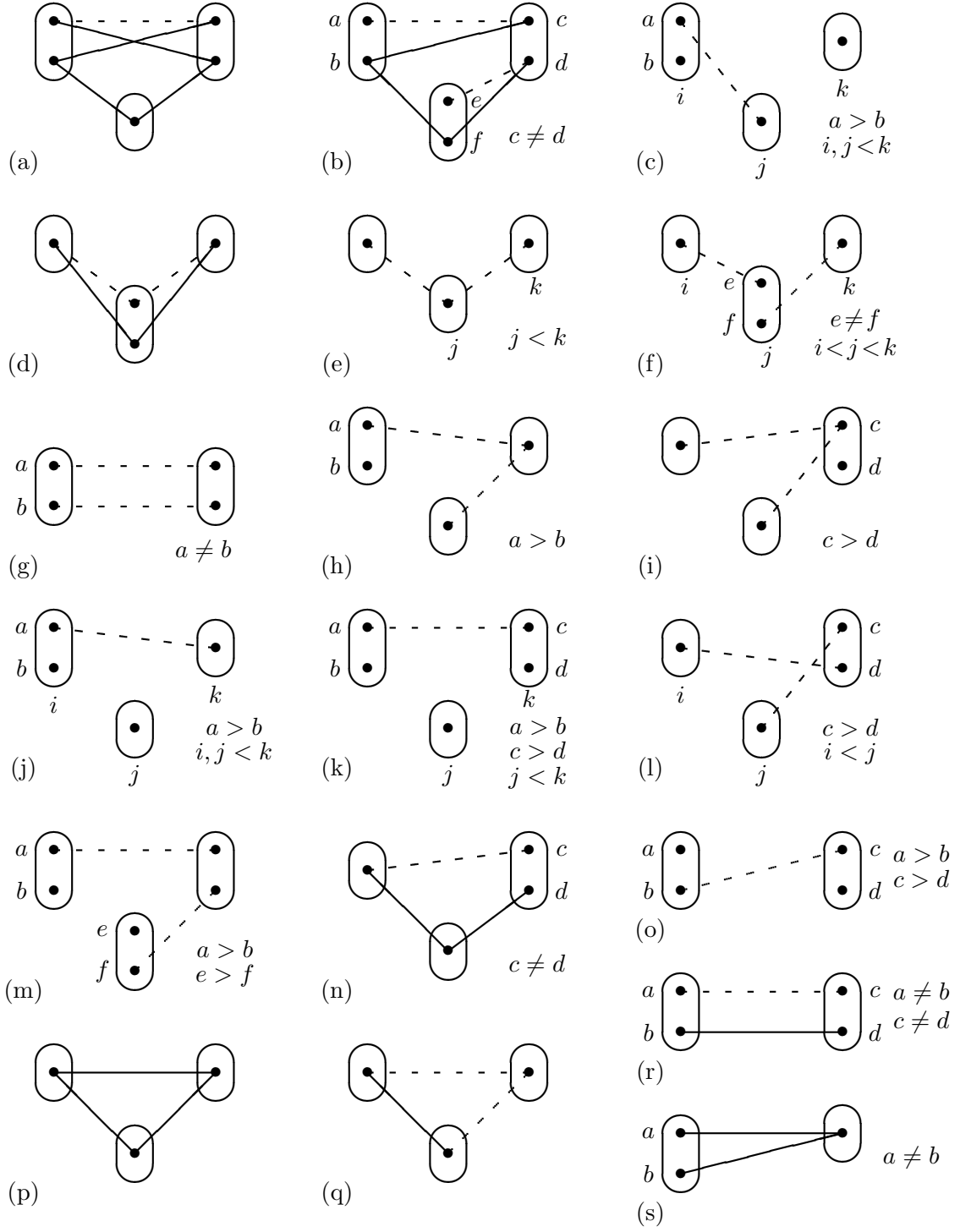


Figure 21: Patterns which do not occur in (a) I_{K4} ; (b) I_4 ; (c) $I_{2\Delta}^{SAT}$; (d),(e),(f) I_5 ; (g),(h),(i) I_6^{SAT} ; (j),(k),(l),(m) I_{K4}^{SAT} ; (n),(o),(p),(q),(r),(s) I_3^{2COL} .

It can easily be verified that the three patterns Figure 21(g), (h), (i) do not occur in I_6^{SAT} . Similarly, the four patterns in Figure 21(j),(k),(l),(m) do not occur in the instance I_{K4}^{SAT} (Figure 20 on page 23).

The instance I_3^{2COL} is the problem of colouring a complete graph on three vertices with only two colours. It is arc consistent but clearly has no solution. It is easy to verify that none of the six patterns in Figure 21(n),(o),(p),(q),(r),(s) occur in I_3^{2COL} . Furthermore, trivially, no pattern on four or more variables occurs in I_3^{2COL} and no pattern with three or more distinct values in the same domain occurs in I_3^{2COL} .

By Lemma 2.5, we know that if there is one of the instances I_{K4} , I_4 , $I_{2\Delta}^{SAT}$, I_5 , I_6^{SAT} , I_{K4}^{SAT} , I_3^{2COL} , such that pattern P does not occur in this instance then P is not AC-solvable. Let P be any of the patterns shown in Figure 21. By Lemma 2.6, any pattern Q in which P occurs is not AC-solvable.

By the pattern in Figure 21(g), a simple AC-solvable pattern cannot contain two negative edges between the same pair of variables. Since instance I_3^{2COL} contains only three variables and instance I_5 contains no triple of variables which have a negative edge between each pair of variables, an AC-solvable pattern can contain *at most three variables and at most two negative edges*. Thus to identify simple AC-solvable patterns we only need to consider patterns on at most three variables, at most two points per variable and with none, one or two negative edges. Furthermore, in the case of two negative edges these negative edges cannot be between the same pair of variables.

5.2. Characterising AC-solvable unordered patterns. In this subsection, we consider only patterns P that have no associated structure (i.e. with $<_X = <_D = \emptyset$). We prove the following characterisation of unstructured AC-solvable patterns.

Theorem 5.1. *If P is a simple unordered pattern, then P is AC-solvable if and only if P occurs in the pattern LX (Figure 13 on page 16) or in the pattern unordered(BTP).*

Proof. By the discussion in Section 5.1, we only need to consider patterns P with at most three variables, at most two points per variable and at most two negative edges (with these edges not being between the same pair of variables). We consider separately the cases of a pattern with 0, 1 or 2 negative edges.

The only simple unordered pattern with no negative edges is the triangle of positive edges shown in Figure 21(p) on page 24 and this pattern is not AC-solvable since it does not occur in I_3^{2COL} .

Let P be a simple pattern with one negative edge (a, c) (between variables y and z) and at most two points per variable. If the domain of y (respectively, z) contains another point b (respectively, d), then for a, b (respectively, c, d) to be non-mergeable, there must be a positive edge (b, c) (respectively, (a, d)). Furthermore, for b (respectively, d) not to be a dangling point, it must belong to another positive edge. Any two distinct points in the domain of a third variable x would be mergeable, so we can assume that P has at most one point in the domain of x . Since this point is not a dangling point, it must be connected by positive edges to at least two points. By a simple exhaustive search we can easily deduce that *either* P is (a subpattern of) a triangle on three variables composed of one negative edge and two positive edges (in which case P occurs in the pattern LX shown in Figure 13 on page 16), *or* one of the patterns shown in Figure 21(a), Figure 21(p) or Figure 21(s) on page 24 occurs in P , in which case, by Lemma 2.6, P is not AC-solvable.

Let P be a simple pattern containing exactly two negative edges (a, b) (between variables x, y) and (a, c) (between variables x, z) that meet at the point a of variable x . Suppose first that x has no other point. If P does not occur in LX , then P must have a positive edge between variables y and z which is either (b, c) or (d, e) where $d \neq b$ and $e \neq c$. In the latter case, to avoid points b, d (respectively, c, e) being mergeable, P must have the positive edge (a, d) (respectively, (a, e)). We can deduce that, if P does not occur in LX , then one of the patterns Figure 21(p) or Figure 21(q) on page 24 occurs in P . Suppose now that P has two points a, f in the domain of variable x . For a, f not to be mergeable, P must have either the positive edge (b, f) or the positive edge (c, f) . If it has both, then the pattern Figure 21(d) on page 24 occurs in P . If P has just one, which without loss of generality we can suppose is the positive edge (b, f) , then for f not to be a dangling point, f must belong to another positive edge (d, f) (where $d \neq b$) or (e, f) (where $e \neq c$). In the latter case, for c, f not to be mergeable, P must also have the positive edge (a, e) . In both cases, the pattern Figure 21(s) on page 24 occurs in P . Thus, if P does not occur in LX , then, by Lemma 2.6, P is not AC-solvable.

Finally, let P be a simple pattern containing exactly two negative edges (a, b) (between variables x, y) and (c, d) (between variables x, z) with two distinct points $a \neq c$ in the domain of variable x . To avoid a, c being mergeable, P must have a positive edge (b, c) or (a, d) . Without loss of generality, suppose P has the positive edge (b, c) . If P does not occur in $\text{unordered}(\text{BTP})$, then at least one of the variables y, z must have two distinct points. If y has a point $e \neq b$, then for b, e not to be mergeable, P must have the positive edge (a, e) . Similarly, if z has a point $f \neq d$, then P must have the positive edge (c, f) . But then, to avoid dangling points, we have to add other positive edges to P and we find that one of the patterns Figure 21(a), Figure 21(n), Figure 21(p) or Figure 21(s) on page 24 occurs in P , and so, by Lemma 2.6, P is not AC-solvable. By Lemma 2.4, if P occurs in $\text{unordered}(\text{BTP})$, then P occurs in BTP , and thus is AC-solvable [16]. \square

5.3. Characterising AC-solvable variable-ordered patterns. In this subsection we consider simple patterns P which have no domain order, (i.e. $<_D = \emptyset$), but do have a partial order on the variables. We first require the following lemma.

Lemma 5.2. *If $P^<$ is a pattern whose only structure is a partial order on its variables and $P^- = \text{unordered}(P^<)$, then*

- (1) $P^<$ is simple if and only if P^- is simple.
- (2) $P^<$ is AC-solvable only if P^- is AC-solvable.

Proof. The property of being simple is (Definition 9) independent of any variable order, hence $P^<$ is simple if and only if P^- is simple. By Lemma 2.4, P^- occurs in $P^<$. The fact that $P^<$ is AC-solvable only if P^- is AC-solvable then follows from Lemma 2.6. \square

Recall pattern $LX^<$ from Example 8 that is obtained from the pattern LX (Figure 13 on page 16) by adding the partial variable order $y < z$. Recall (from Example 8) that the patterns LX and $LX^<$ are, in fact, equivalent.

Lemma 5.2 allows us to give the following characterisation of variable-ordered AC-solvable patterns.

Theorem 5.3. *If P is a simple pattern whose only structure is a partial order on its variables, then P is AC-solvable if and only if P occurs in the pattern $LX^<$ (Example 8), the pattern BTP^{vo} (Figure 4 on page 8) or the pattern $\text{invVar}(\text{BTP}^{vo})$.*

Proof. By Lemma 5.2 and Theorem 5.1, we only need to consider patterns P^- occurring in LX or unordered(BTP) to which we add a partial order on the variables to produce a pattern P .

We first consider the case of a pattern P in which there are two negative edges that meet. By Lemma 5.2 and Theorem 5.1, for P to be AC-solvable, P^- must occur in LX. By Theorem 3.4 and Example 8, we have that $LX^<$ is AC-solvable. Let L be the pattern composed of three variables x, y, z and two negative edges which meet at a point $\langle x, \epsilon \rangle$ (i.e. L is the pattern LX without its positive edges). Then Figure 21(e) on page 24 and Lemma 2.7 tell us that placing any order between x and y or between x and z turns L into a pattern which is not AC-solvable. It follows from Lemma 2.6 that an ordered pattern P containing two negative edges that meet is AC-solvable if and only if P occurs in $LX^<$.

Now consider simple patterns P which contain two negative edges that do not meet. By Lemma 5.2 and Theorem 5.1, for P to be AC-solvable, P^- must occur in unordered(BTP). Adding almost any partial variable order to unordered(BTP) produces a pattern which occurs in BTP^{vo} (Figure 4(b) on page 8) or $\text{invVar}(BTP^{vo})$. The only order for which this is not the case, is the total order $x < z < y$ (or its inverse), where the variables x, y, z are as shown in Figure 4(b) on page 8. Let P be any simple pattern on three variables x, y, z , containing two negative edges (between x, z and y, z) that do not meet and with the variable order $x < z < y$. Then the pattern shown in Figure 21(f) on page 24 occurs in P and hence, by Lemma 2.6, P is not AC-solvable.

If P is any simple pattern such that P^- occurs in LX or unordered(BTP) and contains at most one negative edge, then P occurs in the three-variable triangle pattern composed of one negative and two positive edges; it is then easy to check that, whatever the ordering of variables, P occurs in BTP^{vo} or $\text{invVar}(BTP^{vo})$. \square

5.4. Characterising AC-solvable domain-ordered patterns. In this subsection we consider simple patterns P with a partial order on domains but no ordering on the variables.

Let EMC^- be the no-variable-order version of the pattern EMC depicted in Figure 5 on page 10. We prove the following characterisation of domain-ordered AC-solvable patterns.

Theorem 5.4. *If P is a simple pattern whose only structure is a partial order on its domains, then P is AC-solvable if and only if P occurs in the pattern LX (Figure 13 on page 16), or the pattern EMC^- , or the pattern $\text{invDom}(\text{EMC}^-)$.*

Proof. As in the proofs of Theorem 5.1 and 5.3, we only need to consider patterns on at most three variables, with at most two points per variable and with either no negative edges, one negative edge, two negative edges that meet or two negative edges that do not meet. However, we have more cases to consider than in Theorem 5.1 since patterns may now contain points, such as β in the pattern EMC shown in Figure 5 on page 10, which would be a dangling point without the domain order $\alpha > \beta$.

The only pattern with no negative edges and no mergeable points is the triangle of positive edges shown in Figure 21(p) on page 24 which is not AC-solvable.

Let P be a simple pattern with one negative edge, at most two points per variable and just two variables. If neither of the patterns shown in Figure 21(o) on page 24 and Figure 21(r) on page 24 occur in P , then P occurs in the pattern EMC^- or in $\text{invDom}(\text{EMC}^-)$.

Let P be a simple pattern on three variables x, y, z , with one negative edge (a, c) (between variables y and z) and at most two points per variable. If the domain of y

(respectively, z) contains another point b (respectively, d), then for a, b (respectively, c, d) to be non-mergeable, there must be a positive edge (b, c) (respectively, (a, d)). Any two distinct points in the domain of variable x would be mergeable, so we can assume that P has exactly one point in the domain of x . Since this point e is not a dangling point, it must be connected by positive edges to at least two points. If none of the patterns in Figure 21(a), Figure 21(p) and Figure 21(s) on page 24 occurs in P , then e must belong to the two positive edges (a, e) and (c, e) , and no others. If neither of the patterns in Figure 21(o) or Figure 21(r) on page 24 occurs in P , then we can deduce that P occurs in the pattern EMC^- or in $\text{invDom}(\text{EMC}^-)$.

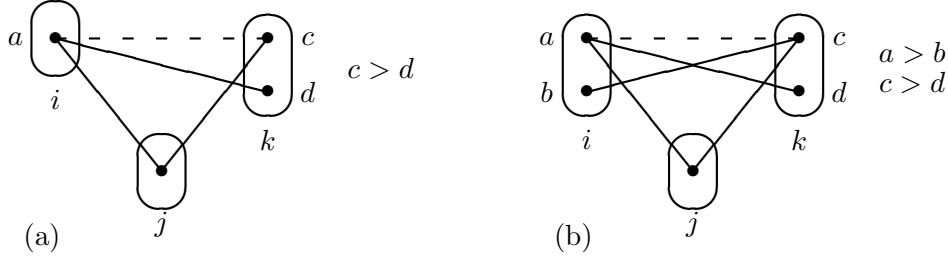
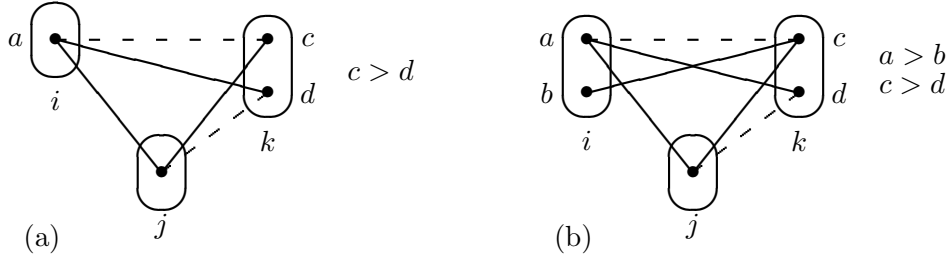
Let P be a simple pattern on three variables with at most two points per variable and with two negative edges that meet. If P has two points a, b in the domain of the same variable together with an ordering $a < b$, then one of the patterns in Figure 21(h) and Figure 21(i) on page 24 (or their domain-inversed version) occurs in P , and hence P cannot be AC-solvable. This leaves only the case of unordered patterns P . By the proof (and in particular the part that deals with patterns containing exactly two negative edges that meet) of Theorem 5.1, we can deduce that if P is AC-solvable then it occurs in the pattern LX.

Let P be a simple pattern on three variables x, y, z with at most two points per variable and with two negative edges (a, c) (between variables x and y) and (d, f) (between variables y and z) that do not meet (i.e. $c \neq d$). If P contains only these four points a, c, d, f , then it necessarily occurs in EMC^- . If P contains exactly five points, then without loss of generality, we can assume that there is a point $b \neq a$ in the domain of x . Since a, b are not mergeable, there must be a positive edge (b, c) in P . If P has a positive edge (b, f) , then the pattern in Figure 21(n) on page 24 occurs in P ; if P has a positive edge (b, d) then the pattern in Figure 21(s) on page 24 occurs in P . Now, if the pattern in Figure 21(o) on page 24 does not occur in P , then whatever ordering is placed on a, b and c, d , P occurs in the pattern EMC^- or in $\text{invDom}(\text{EMC}^-)$. If P contains exactly six points, then there must be points $b \neq a$ in the domain of x and $e \neq f$ in the domain of z . Since both a, b and e, f , are not mergeable, there must be positive edges (b, c) and (e, d) . If P has a positive edge (b, e) , then the pattern in Figure 21(b) on page 24 occurs in P ; if P has a positive edge (b, f) or (a, e) , then the pattern in Figure 21(n) on page 24 occurs in P ; if P has a positive edge (b, d) or (e, c) , then the pattern in Figure 21(s) on page 24 occurs in P . But then in all other cases one of b and e is a dangling point unless P has an order on both a, b and e, f . But this then implies that at least one of the patterns in Figure 21(m) and Figure 21(o) on page 24 occur in P . In all these cases, by Lemma 2.6, P is not AC-solvable. \square

5.5. Characterising AC-solvable ordered patterns. In this subsection we consider the most general case of simple patterns P which have a partial domain order and a partial variable order. We prove the following characterisation of AC-solvable patterns with partial orders on domains and variables.

Theorem 5.5. *If P is a simple pattern with a partial order on its domains and/or variables, then P is AC-solvable if and only if P occurs in one of the patterns $\text{LX}^<$, EMC (Figure 5 on page 10), BTP^{vo} , BTP^{do} (Figure 4 on page 8), BTX (Figure 9 on page 14) or BTI (Figure 10 on page 14) (or versions of these patterns with inversed domain-order and/or variable-order).*

Proof. Let P^- be the same pattern as P but without the partial order on its variables. If P is AC-solvable, then, by Lemma 2.4, P^- occurs in P , and hence, by Lemmas 2.3 and 2.5,

Figure 22: One-negative-edge patterns occurring in EMC^- .Figure 23: Two-negative-edge patterns occurring in EMC .

P^- is also AC-solvable. Thus, by Theorem 5.4, P^- must occur in either LX , EMC^- or $\text{invDom}(\text{EMC}^-)$. We consider the four cases: no negative edges, one negative edge, two negative edges that meet, two negative edges that do not meet in P . We have already seen in the proofs of Theorems 5.1 and 5.4 that there are no simple AC-solvable patterns with only positive edges, so there remain three cases to consider.

Let P be a simple pattern with exactly one negative edge. If P^- (which also has one negative edge) occurs in LX and is simple (and hence has no dangling points) then it must occur in a triangle T consisting of one negative and two positive edges. This triangle pattern T occurs in BTP or in $\text{invVar}(\text{BTP})$ whatever ordering we place on its three variables and hence the same is true of P . If P^- (which has one negative edge and is unmergeable) occurs in EMC^- but not in the triangle T , then P^- occurs in one of the two patterns shown in Figure 22 on page 29 (or the domain-inversed versions of these patterns) and includes the point d (in the case corresponding to Figure 22(a) on page 29) or the points b and d (in the case corresponding to Figure 22(b)) on page 29. For d (respectively, b) not to be a dangling point in P , we must have the order $c > d$ (respectively $a > b$) in P . If P^- occurs in the pattern in Figure 22(a) on page 29 and P has the variable order $i, j < k$ (or $i < k$ or $j < k$), then P occurs in BTP^{do} . If P^- occurs in the pattern in Figure 22(a) on page 29 and P has the variable order $i < j$, then P occurs in $\text{invVar}(\text{BTI})$. If P^- occurs in the pattern in Figure 22(a) on page 29 and P includes the variable order $i < j, k$ and domain order $c > d$, then the pattern in Figure 21(j) on page 24 occurs in $\text{invVar}(P)$. If P^- occurs in the pattern in Figure 22(a) on page 29 and P includes the variable order $i, k < j$ and domain order $c > d$, then the pattern in Figure 21(c) on page 24 occurs in P . This covers all variable orderings of P (after taking into account the variable-inversed versions of each case) when P^- occurs in the pattern in Figure 22(a) on page 29. Now consider the case in which P^- occurs in the pattern in Figure 22(b) on page 29. If P includes the variable order $j < k$ (or

$j < i$) together with the domain order $a > b$ and $c > d$, then the pattern in Figure 21(k) on page 24 occurs in P . If P has the variable order $i < k$ then P occurs in EMC. Thus all one-negative-edge AC-solvable patterns occur in BTP, BTI or EMC (or their domain and/or variable-inversed versions).

Let P be a simple pattern with two negative edges that meet at a point. P^- necessarily occurs in the pattern LX. Let j be the variable of P where the two negative edges meet, and let i, k be the other two variables. If P includes the variable order $j < k$ (or, by symmetry, the order $j < i$), then the pattern in Figure 21(e) on page 24 occurs in P and hence P is not AC-solvable. If P has the variable order $i < k$, then P occurs in the pattern $LX^<$ (the version of LX shown in Figure 13 on page 16 together with the variable order $y < z$). By symmetry, we have covered all possible cases.

Finally, let P be a simple pattern with two negative edges that do not meet at a point. P^- necessarily occurs in the pattern EMC. We distinguish two distinct cases: (1) P^- occurs in the pattern in Figure 23(a) on page 29 or (2) P^- occurs in the pattern in Figure 23(b) on page 29 and includes the point b together with the order $a > b$ (otherwise b would be a dangling point). We first consider case (1). If P includes the order $c > d$ and $i < j$, then the (inversed domain-order version of the) pattern in Figure 21(l) on page 24 occurs in P and hence P is not AC-solvable. If P includes the order $i < k < j$, then the pattern in Figure 21(f) on page 24 occurs in P . If P has the variable order $i < j < k$ and no domain order, then P occurs in BTP^{vo} . If P has the variable order $i, j < k$ and the domain order $c > d$, then P occurs in BTP^{do} . All other patterns which fall in case (1) are covered by symmetry. Now we consider the case (2). First suppose that P includes the domain order $c > d$ (as well as $a > b$). If P includes the variable order $i < j$, then the (domain-inversed version of the) pattern in Figure 21(l) on page 24 occurs in P . If P includes the variable order $j < k$, then the pattern in Figure 21(k) on page 24 occurs in P . If P has the variable order $i < k$, then P occurs in EMC. Now, suppose that P does not include the domain order $c > d$. If P includes the variable order $i, j < k$, then the pattern in Figure 21(j) on page 24 occurs in P . If P includes the variable order $i, k < j$, then the pattern in Figure 21(c) on page 24 occurs in P . If P has the variable order $i < j, k$ (or $i < j$ or $i < k$) then P occurs in BTX. If P has the variable order $j < k$ then P occurs in BTI. By symmetry we have covered all possible variable orderings of P in case (2). \square

6. CONCLUSION

We have identified 4 new tractable classes of binary CSPs. Moreover, we have given a characterisation of all simple partially-ordered patterns decided by AC. We finish with open problems.

For future work, we plan to study the wider class of unmergeable ordered patterns in which two points a, b may be non-mergeable simply because there is an order $a < b$ on them. In the present paper, a, b are mergeable unless they have different compatibilities with a third point c .

Is there a way of giving a unified description of EMC, BTX and BTI, since to find a solution after establishing arc consistency we use basically the same algorithm? Any such generalisation will not be a simple forbidden pattern by Theorem 5.5, but there is possibly some other way of combining these patterns.

Are there interesting generalisations of these patterns to constraints of arbitrary arity, valued constraints, infinite domains or QCSP? BTP has been generalised to constraints of arbitrary arity [18] as well as to QCSPs [26]. Max-closed constraints have been generalised to VCSPs [12]. Infinite domains is an interesting avenue of future research because simple temporal constraints are binary max-closed [23].

In this paper, we only focused on classes of CSP instances with totally ordered domains (but defined by partially-ordered patterns). However, the framework of forbidden patterns captures language-based CSPs with partially-ordered domains, such as CSPs with a semi-lattice polymorphism. In the future, we plan to investigate classes of CSP instances with partially-ordered domains.

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REFERENCES

- [1] Albert Atserias, Andrei A. Bulatov, and Víctor Dalmau. On the Power of k -Consistency. In *Proceedings of the 34th International Colloquium on Automata, Languages and Programming (ICALP'07)*, volume 4596 of *Lecture Notes in Computer Science*, pages 279–290. Springer, 2007.
- [2] Libor Barto. Constraint satisfaction problem and universal algebra. *ACM SIGLOG News*, 1(2):14–24, 2014.
- [3] Libor Barto and Marcin Kozik. Constraint Satisfaction Problems Solvable by Local Consistency Methods. *Journal of the ACM*, 61(1), 2014. Article No. 3.
- [4] Christian Bessière, Jean-Charles Régin, Roland H. C. Yap, and Yuanlin Zhang. An optimal coarse-grained arc consistency algorithm. *Artif. Intell.*, 165(2):165–185, 2005.
- [5] Andrei Bulatov. Combinatorial problems raised from 2-semilattices. *Journal of Algebra*, 298:321–339, 2006.
- [6] Andrei Bulatov. Bounded relational width. Unpublished manuscript, 2009.
- [7] Andrei Bulatov and Víctor Dalmau. A simple algorithm for Mal'tsev constraints. *SIAM Journal on Computing*, 36(1):16–27, 2006.
- [8] Andrei Bulatov, Peter Jeavons, and Andrei Krokhin. Classifying the Complexity of Constraints using Finite Algebras. *SIAM Journal on Computing*, 34(3):720–742, 2005.
- [9] Clément Carbonnel and Martin C. Cooper. Tractability in constraint satisfaction problems: a survey. *Constraints*, 21(2):115–144, 2016.
- [10] David A. Cohen, Martin C. Cooper, Guillaume Escamocher, and Stanislav Živný. Variable and value elimination in binary constraint satisfaction via forbidden patterns. *Journal of Computer and System Sciences*, 81(7):1127–1143, 2015.
- [11] David A. Cohen, Martin C. Cooper, Peter Jeavons, and Stanislav Živný. Tractable classes of binary CSPs defined by excluded topological minors. In *Proceedings of the 24th International Joint Conference on Artificial Intelligence (IJCAI'15)*, pages 1945–1951. AAAI Press, 2015.
- [12] David A. Cohen, Martin C. Cooper, Peter G. Jeavons, and Andrei A. Krokhin. The Complexity of Soft Constraint Satisfaction. *Artificial Intelligence*, 170(11):983–1016, 2006.
- [13] Martin C. Cooper, David A. Cohen, Páidí Creed, Dániel Marx, and András Z. Salamon. The tractability of CSP classes defined by forbidden patterns. *Journal of Artificial Intelligence Research*, 45:47–78, 2012.
- [14] Martin C. Cooper, Simon de Givry, Martí Sánchez, Thomas Schiex, Matthias Zytnicki, and Tomáš Werner. Soft arc consistency revisited. *Artificial Intelligence*, 174(7–8):449–478, 2010.
- [15] Martin C. Cooper and Guillaume Escamocher. Characterising the complexity of constraint satisfaction problems defined by 2-constraint forbidden patterns. *Discrete Applied Mathematics*, 184:89–113, 2015.
- [16] Martin C. Cooper, Peter G. Jeavons, and András Z. Salamon. Generalizing constraint satisfaction on trees: Hybrid tractability and variable elimination. *Artificial Intelligence*, 174(9–10):570–584, 2010.
- [17] Martin C. Cooper, Philippe Jégou, and Cyril Terrioux. A Microstructure-Based Family of Tractable Classes for CSPs. In *Proceedings of the 21st International Conference on Principles and Practice of*

- Constraint Programming (CP'15)*, volume 9255 of *Lecture Notes in Computer Science*, pages 74–88. Springer, 2015.
- [18] Martin C. Cooper, Achref El Mouelhi, Cyril Terrioux, and Bruno Zanuttini. On broken triangles. In *Proceedings of the 20th International Conference on Principles and Practice of Constraint Programming (CP'14)*, volume 8656 of *Lecture Notes in Computer Science*, pages 9–24. Springer, 2014.
 - [19] Martin C. Cooper and Stanislav Živný. The power of arc consistency for CSPs defined by partially-ordered forbidden patterns. In *Proceedings of the 31st Annual ACM/IEEE Symposium on Logic in Computer Science (LICS'16)*, pages 652–661, 2016.
 - [20] Martin C. Cooper and Stanislav Živný. Hybrid tractable classes of constraint problems. In Andrei Krokhin and Stanislav Živný, editors, *Complexity and approximability of Constraint Satisfaction Problems*, volume 7 of *Dagstuhl Follow-Ups*, pages 113–135. Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2017.
 - [21] M.C. Cooper. Linear-time algorithms for testing the realisability of line drawings of curved objects. *Artificial Intelligence*, 108:31–67, 1999.
 - [22] Víctor Dalmau. Generalized Majority-Minority Operations are Tractable. *Logical Methods in Computer Science*, 2(4), 2006.
 - [23] R. Dechter, I. Meiri, and J. Pearl. Temporal constraint networks. *Artif. Intell.*, 49:61–95, 1991.
 - [24] Guillaume Escamocher. *Forbidden Patterns in Constraint Satisfaction Problems*. PhD thesis, University of Toulouse, 2014.
 - [25] Tomás Feder and Moshe Y. Vardi. The Computational Structure of Monotone Monadic SNP and Constraint Satisfaction: A Study through Datalog and Group Theory. *SIAM Journal on Computing*, 28(1):57–104, 1998.
 - [26] Jian Gao, Minghao Yin, and Junping Zhou. Hybrid tractable classes of binary quantified constraint satisfaction problems. In *Proceedings of AAAI'11*. AAAI Press, 2011.
 - [27] Martin J. Green and David A. Cohen. Domain permutation reduction for constraint satisfaction problems. *Artificial Intelligence*, 172(8-9):1094–1118, 2008.
 - [28] Martin Grohe. The complexity of homomorphism and constraint satisfaction problems seen from the other side. *Journal of the ACM*, 54(1):1–24, 2007.
 - [29] Paweł M. Idziak, Petar Marković, Ralph McKenzie, Matthew Valeriote, and Ross Willard. Tractability and learnability arising from algebras with few subpowers. *SIAM Journal on Computing*, 39(7):3023–3037, 2010.
 - [30] Peter G. Jeavons and Martin C. Cooper. Tractable Constraints on Ordered Domains. *Artificial Intelligence*, 79(2):327–339, 1995.
 - [31] Vladimir Kolmogorov, Michal Rolínek, and Rustem Takhanov. Effectiveness of structural restrictions for hybrid csp. *CoRR*, abs/1504.07067, 2015.
 - [32] Vladimir Kolmogorov, Johan Thapper, and Stanislav Živný. The power of linear programming for general-valued CSPs. *SIAM Journal on Computing*, 44(1):1–36, 2015.
 - [33] Dániel Marx. Tractable hypergraph properties for constraint satisfaction and conjunctive queries. *Journal of the ACM*, 60(6), 2013. Article No. 42.
 - [34] Wady Naanaa. Unifying and extending hybrid tractable classes of CSPs. *Journal of Experimental and Theoretical Artificial Intelligence*, 25(4):407–424, 2013.
 - [35] Francesca Rossi, Peter van Beek, and Toby Walsh, editors. *The Handbook of Constraint Programming*. Elsevier, 2006. Chapter 3 (by Christian Bessière): Constraint Propagation.
 - [36] Rustem Takhanov. Hybrid (V)CSPs and algebraic reductions. *CoRR*, abs/1506.06540, 2015.
 - [37] Johan Thapper and Stanislav Živný. The complexity of finite-valued CSPs. *Journal of the ACM*, 63(4), 2016. Article No. 37.